GEOPHYSICS

VOL. XXII, NO. 2 APRIL, 1957

Geophysics—Full Partner ..... *Morgan J. Davis* 225
Sound Propagation in Compacted Ocean Sediments ..... *A. S. Laughton* 233
The Structure of the Noise Background of a Seismogram II ..... *C. W. Horton* 261
Attenuation of Sound in Rocks ..... *M. Krishnamurthi and S. Balakrishna* 268
A Seismic Model Study of the Phase Velocity Method of Exploration ..... *Frank Press* 275
The Gulf Seismic Profile Printer ..... *E. M. Palmer* 286
A Problem in the Analysis of Geophysical Data ..... *Fraser Grant* 309
Note on an Application of Sonar to the Shallow Reflection Problem ..... *Isidore Zietz and L. C. Pakiser* 345
Submarine Gravity Detailing, San Luis Pass Dome, Brazoria County, Texas ..... *L. L. Nettleton* 348
A New Method for Interpretation of Aeromagnetic Maps: Pseudo-Gravimetric Anomalies ..... *V. Baranov* 359
Polar Movement as Indicated by Rock Magnetism ..... *Lynn G. Howell and Joseph D. Martinez* 384
Resistivity Studies of Metalliferous Synthetic Cores ..... *Peter Mandel, Jr., J. W. Berg, Jr., and Kenneth L. Cook* 398
Geophysical Research and Progress in Exploration ..... *Milton B. Dobrin and Henry P. Dunlap* 412
Report of SEG Subcommittee on Information on Magnetic Recorder Characteristics ..... *S. Kaufman, A. L. Perrack, and J. D. Shelton* 434

DEPARTMENTS

Patents 442
Reviews and Publications Received 453

Memorials

Charles Andrew Arsenault ..... *Brooks Stewart* 459
Donald Crary ..... *Roy F. Bennett* 461
Everette Lee DeGolyer ..... *J. C. Karcher* 463
Robert Treat Paine Thompson ..... *Cecil H. Green* 466

Contributors 468

Society Round Table

Committees 477
Local Sections 478
Membership Applications Received 482
26th Annual Meeting 484
Abstracts of Papers Presented at the 26th Annual Meeting 495
Nominees for 1957-1958 Executive Committee 507
Announcements 512
Personal Items 519

Calendar of Meetings 522

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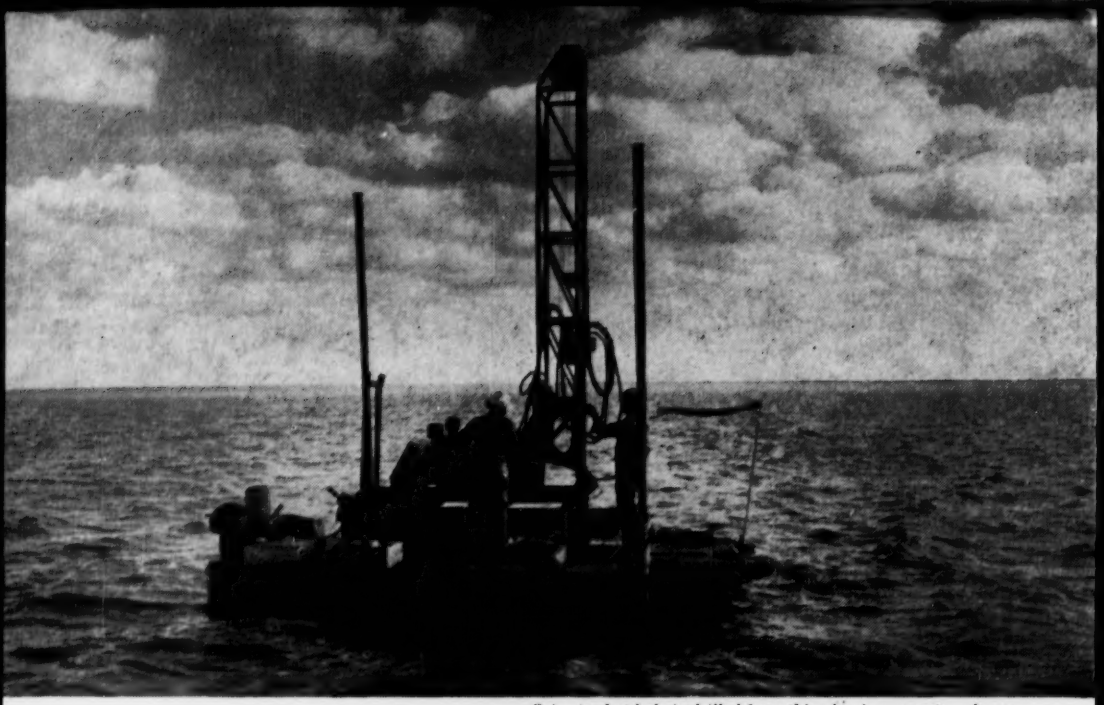

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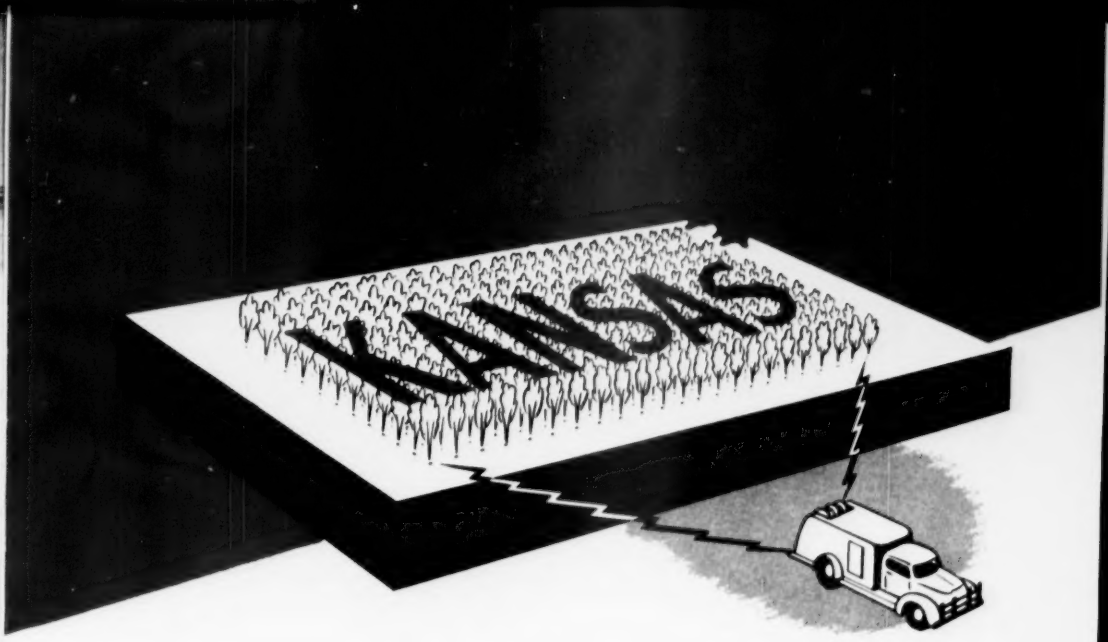

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Decca Navigator Co., Ltd. 36
DuPont—Explosives Dept. 6-7
DuPont—Photo Products 74-75

EAEG 34
Eastman Kodak Co. 25
Economic Geology 26
Elder Trailer & Body, Inc. 32
Electrodynamic Instrument Corp. 42
Electro-Tech International 10-11
Electro-Technical Labs. 14-15, 52, 81

Fairchild Aerial Surveys, Inc. 62

General Geophysical Co. 31
Geophysical Associates International ... 56
Geophysical Instr. & Supply Co. 78
Geophysical Service, Inc. ..... 4th cover
Geophysical Society of Tulsa 32
Geophysical Specialties Co. 12
Gravity Meter Expl. Co. ..... Insert
Griffin Tank & Welding Service ..... Insert

Harper & Brothers, Inc. 76
Harrison Equipment Co. 68
Herb J. Hawthorne, Inc. 8

Kern Instruments, Inc. ... See R. L. Sargent
Klaus Exploration Co. 41
Koenig Iron Works 29

Lane-Wells Company 49

Mayes-Bevan Company 39
Mayhew Supply Co., Inc. ..... Insert
E. V. McCollum & Co. 61
McCollum Exploration Co. 43
Mid-Continent Geophysical Co. 45
Mission Manufacturing Co. ..... Insert
Mount Sopris Instrument Corp. 66

National Geophysical Co. ..... 2nd cover
North American Geophysical Co. 54

Oklahoma Geophysical Co. 9

Petroleum Geophysical Co. 64
Petty Geophysical Engineering Co. 67
Prakla 35

Robert H. Ray Co. 55
Rayflex Exploration Co. 27
Republic Exploration Co. 51
Rogers Geophysical Co. 47
Ruska Instrument Corp. 60
R. L. Sargent Co. 46

SEG 78, 80
Schlumberger Well Surveying Corp. ... 57
Seismic Engineering Co. 28
Seismic Explorations, Inc. 53
Seismograph Service Corp. ..... 3rd cover
Seismos GmbH 73
Sharpe Instruments, Ltd. 38
Southern Geophysical Co. 48
S.W. Industrial Electronics Co. ... 77, Insert
Spang & Company 4
Surveyors Service Co. 4

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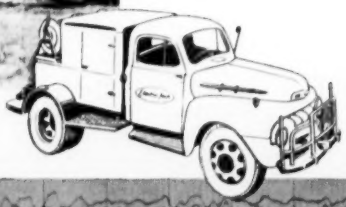

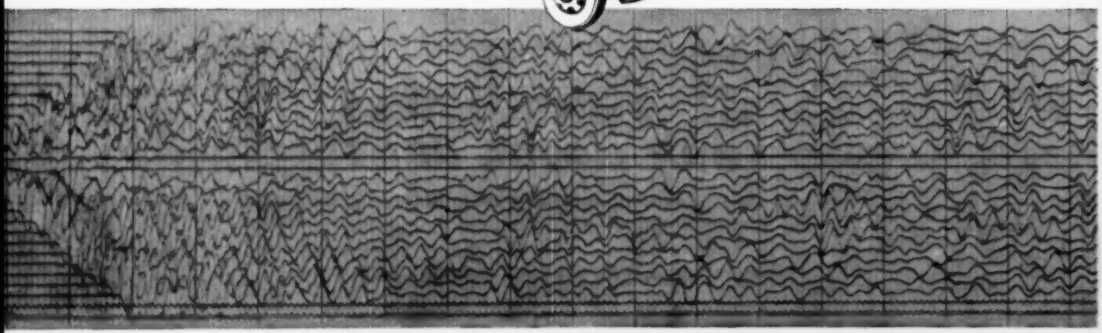

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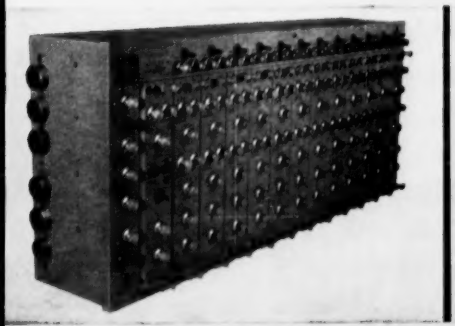

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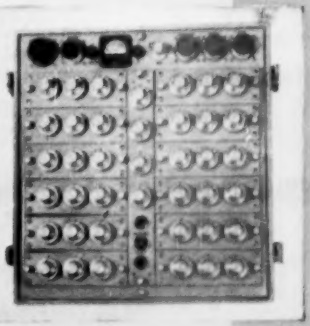

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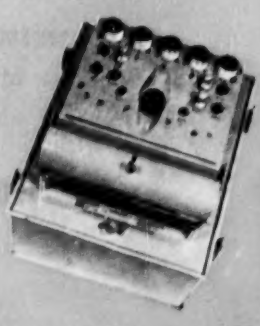

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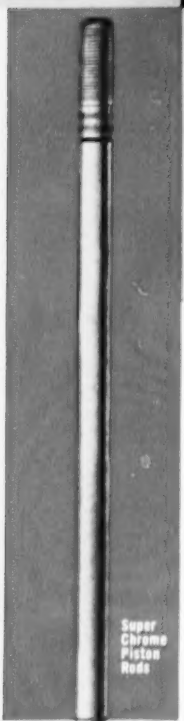

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GEOPHYSICS—FULL PARTNER*

MORGAN J. DAVIS†

The advent of exploration geophysics in the United States was in late 1922 when torsion balances were brought over to the United States from Germany by both the Roxana (the predecessor of Shell) and the Amerada Petroleum Corporation. The first survey in the Gulf Coast of Texas was at Spindletop in December, 1922, under the direction of Donald C. Barton, who later and at the time of his death in 1939 was Humble's chief research geologist. It was Donald Barton's idea that the known shallow piercement-type salt dome at Spindletop would furnish a testing ground for this new method. It should be recorded that an excellent anomaly was found in this survey. Discouraging results followed, however, as other known structures were found to give no significant anomaly, and in other instances where anomalous areas were outlined they were condemned by the drilling of exploratory wells. In March, 1924—about a year and a half later—however, an outstanding anomaly was found in the Nash area, Fort Bend County, Texas. In November of that same year dome material was found by the drill, and the discovery of the Nash Dome was a reality. It was not until January 3, 1926, though, that oil was found on the flank of the dome, and this is probably the first oil found as a result of the use of geophysical methods in the United States.

Only a little later than the introduction of the torsion balance, the refraction seismograph had been introduced into the coastal area in an experimental fashion. Its early history of discouragement was quite parallel to that of the gravity instrument, as the refraction seismic anomalies generally were not found to coincide with known structures. The introduction of fan-type shooting by L. P. Garrett of Gulf changed this situation, however, and in October, 1924, the Orchard Dome—also in Fort Bend County, Texas—was discovered.

Improvement in the interpretation of results from both the torsion balance and the refraction seismograph was rapid, and by the end of 1926 the coastal area of Texas and Louisiana experienced an exploration boom. Some forty piercement domes were discovered in less than four years, but by the end of 1930 the refraction boom had virtually ended, as it had found most of the domes the still

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rather primitive instrument was capable of mapping. It is interesting to note that it was not until many years later that the refraction seismograph again became one of the reliable geophysical tools—and this only after much improvement in techniques and instrumentation.

Fortunately the reflection seismograph was being developed during the same period when the refraction method was in the height of its success, and it first demonstrated its ability to find structure successfully in 1927. It was fortunate that as the refraction method faded out of the picture, the reflection seismograph took over and continued to find structures which the early refraction method could not discover. It early demonstrated its utility in mapping the "deep-seated" type of coastal structures which eventually furnished some of the largest fields of this prolific area. From a modest beginning of less than 10 crews even by the end of 1930, reflection seismic exploration had become so successful by 1937 that the industry was running over 200 crews in the United States.

Gravity methods experienced ups and downs throughout the late twenties and the thirties. In 1930 the gravity meter was first introduced by Humble, and since it accomplished the work of the torsion balance at a fraction of the cost and with much greater rapidity, it so quickly made the torsion balance obsolete that by the end of 1936 its use was, for all practical purposes, discontinued. The gravity meter has, of course, been improved since that time but is basically the same instrument as that used at the start.

The history of the introduction of the magnetometer, which first came into general use in 1924, is very similar to that described for the gravity methods. The magnetometer, however, cannot be said to have had a "boom" during the many years it has been employed, although it has been steadily used since its advent. The development of the flying magnetometer by Gulf and the availability of this service to others has, of course, caused a revival of interest in this method.

I think it is fair to say that even for some period of time after all three of the principal geophysical instruments came into general use they were regarded as innovations, largely experimental, and by many even as gadgets. At best it was hoped that they would supplement more orthodox geologic interpretations or could be used to piece together structural knowledge of areas masked by disconformable rocks.

As technological improvements and better interpretation of results were realized in all geophysical methods, and particularly in the seismograph, success in finding new oil and gas fields became impressive in the United States in the thirties, as already shown, and on up to the beginning of World War II. That great international disaster slowed down all exploration, although an active geophysical campaign was carried on throughout the conflict.

During this golden age of geophysics, the so-called "doodlebugs," those gadgets which had been smiled on tolerantly by the industry at the beginning, became the favored method of oil-finding to such an extent that other exploration methods were sometimes abandoned or neglected, and some exploration managers

often preferred seismic maps notwithstanding the contrary testimony of surface and subsurface geology. I can well remember my amazement when visiting a crew in one of the western states to find that a seismic line was being run across an anticline on which the opposing dip slopes were so pronounced that a sophomore in geology would have needed no more than a Brunton compass to map the structure accurately! During that period it was regarded as a poor prospect, indeed, that did not have a seismic picture!

Concurrent with the sensational rise of geophysics in the United States there developed, as might have been expected, a keen rivalry between geologists and geophysicists. While competition is usually a good thing, this rivalry manifested itself to such a degree that in many cases there was no real coordination of the work of the two exploration groups—the geophysicists and the geologists—and a regrettable lack of communication between them. As an illustration of this situation, in some organizations even managers of exploration were known to give instructions to geophysicists and geologists not to compare their results nor discuss interpretations arrived at separately by the two groups. The result was that sometimes when exploration expenditures were planned, the responsible executives were forced to arrive at a decision after studying two sets of maps—one geophysical, the other geological—on which the same areas of interest were mapped in such a way that there was little resemblance, if any, between the structural conditions shown on the different maps. It was small wonder, then, that during this period when even management sometimes discouraged cooperation, there was often no real teamwork carried on by these two principal exploration groups. One wonders how many potential discoveries were passed by in those years before there was a pooling of *all* the information—structural, paleontologic, stratigraphic, gravimetric, magnetic, and seismic—which would have contributed to a better over-all interpretation and understanding of regional geology and individual prospects.

The situation described was one which could not long exist, and thoughtful geologists and geophysicists began effective work to improve the relationship beginning many years ago. By early 1952 so much improvement had occurred that, in reporting to the membership of AAPG while president of that association, I attempted to describe the importance of the teamwork between the two groups as follows:

"The significance of the high degree of cooperation between the geophysical and geological groups in many modern exploration organizations cannot be overemphasized. Between the two groups, a new spirit of teamwork now exists which has largely replaced an older attitude of indifference, and sometimes even of antagonism. With the team spirit there has also come a feeling of mutual respect and appreciation of each other's work. This cooperation has been reflected by a striking increase in finding efficiency."

Even in the past four years tremendous additional progress has been made. Not the least of the reasons for the bettering of the relationship has been the

growing number of geophysicists in managerial and supervisory positions who have had formal training in and an understanding of geology. Likewise there is an increasing number of geologists who have included a number of courses in physics or geophysics in their college curricula and/or who have served on geophysical crews as a part of their training. Therefore, we may say that better education and training of exploration personnel has played an important part in the creation of the desired team spirit which, I believe, in most cases now actuates the exploration effort of the industry. While there still may be cases of less than full cooperation in some organizations, I believe they are unusual and diminishing.

The practice of geology as directed toward oil and gas finding is not an old profession as professions go. Actually the petroleum geologist, *per se*, did not get much more than a 20-year headstart over his exploration associate, the petroleum geophysicist. However, the latter has progressed at a phenomenal pace. Never has a profession grown more rapidly! From a start of 2 crews in 1922, world-wide geophysical activity in petroleum had expanded to over 1,100 crews in 1955, as shown in the January issue of GEOPHYSICS.

The profession passed through the early stages of trial and error, experienced the expected setbacks and false starts, but regardless of the fluctuations on the curve, the trend has been steadily upward. All of us in the industry have known now for a number of years that the profession of geophysics has been and is a scientific, sound, and indispensable member of the petroleum exploration team, but the point I wish to emphasize this morning is that geophysics is not just a member of the team—it is more than that, much more; it is a partner—*full partner*—in this vital business of finding oil!

And how fortunate it is that the petroleum geophysicist and the petroleum geologist each finds that he has a trusted and respected partner—full partner—in these days when the world we live in is just now becoming really aware of its burgeoning present and future requirements for energy!

You have all read the different estimates of future energy requirements that have recently been coming out at regular intervals, and you all know that most forecasters agree that the demand for petroleum will continue to grow almost indefinitely notwithstanding the probability that energy from nuclear and other sources may, within our lifetime, supply an appreciable part of the growth in total energy requirements. Estimates of future demand for petroleum in the United States vary. Wallace E. Pratt believes that in 1975 the demand for petroleum in the United States may average 13.5 million barrels per day. Joseph E. Pogue and others have suggested a possible demand of 12.8 million barrels per day in the United States by as early as 1965.

Where disagreement arises is not on the question of demand but on whether the industry can continue to find the oil to meet that demand. There is, of course, no way that this question can be categorically answered. I have long leaned toward the optimistic side, however, and I believe that industry statistics support my view. Some recent compilations from published sources show that

while the ratio of oil wells to total completions has declined somewhat during the last three decades, the total new oil found in the United States, as well as the net additions to reserves, has increased substantially during the subject period, with the last decade by far the best. This is shown in Figure 1. This graph may surprise those who are sometimes prone to speak of the "golden thirties" in nostalgic tones!

The correlation between oil well completions, or total completions, and new

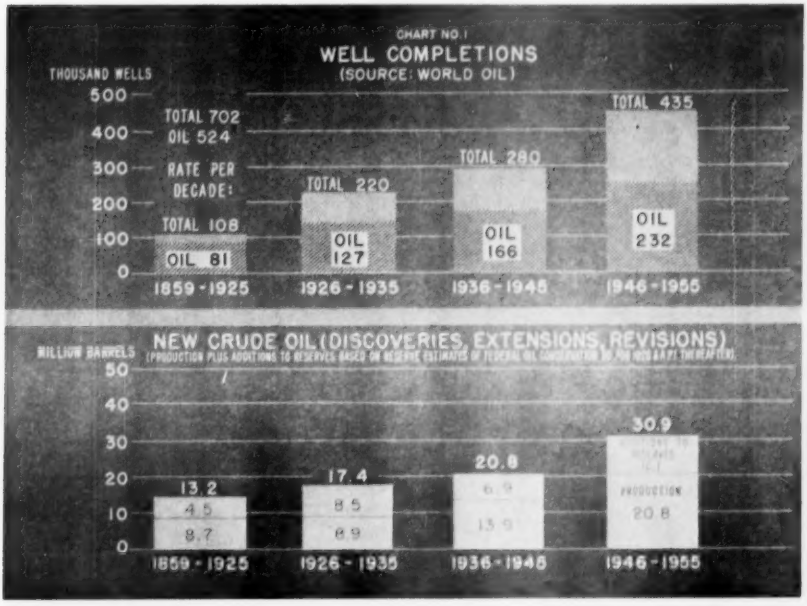

FIG. 1

crude oil found is always interesting and has been commented upon by many industry students. Figure 2 contains data of a recent compilation showing a small decline during the last three decades when total new oil is divided by total completions and reduced to a per well basis. The new crude oil per oil well completion, however, shows a different pattern with the last decade again showing higher reserves per oil well than in the late thirties and early forties. Figure 3 again shows the remarkably uniform volume of new oil on a per well basis when distributed to oil well completions over the past 20 years—about 130,000 barrels per well. The industry will complete close to 32,000 oil wells in 1956. It will be surprising if the average annual number of oil well completions over the next decade does not exceed this level. Even if the average does not exceed the 1956

number, however, the oil wells to be drilled in the ten years should furnish over 40 billion barrels of new oil, provided, of course, new oil wells continue to develop about the same amount of oil as the strikingly consistent record of the past twenty years This would make it possible for production to increase at the same rate as demand and to increase proved reserves in proportion to production.

But these are mere statistics, however impressive they may be. The real reason I am optimistic regarding our ability to find the oil needed at least

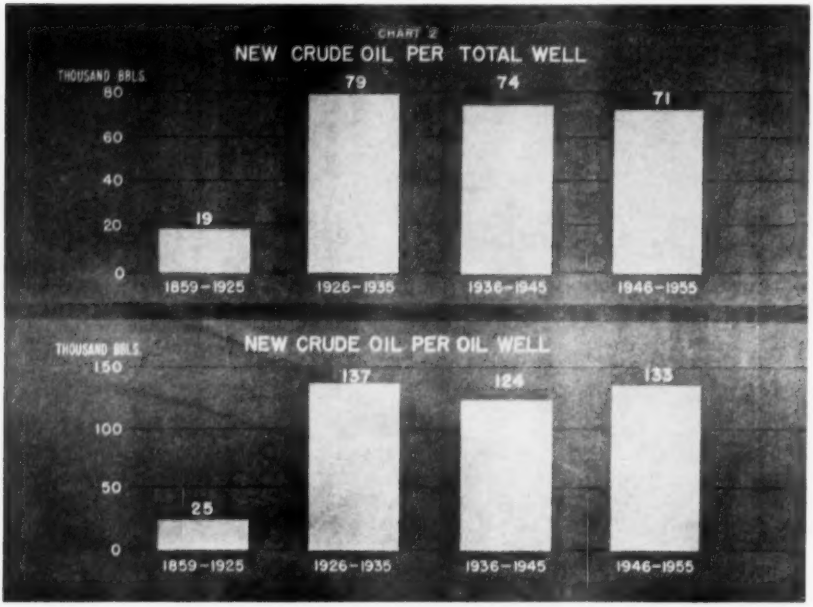

FIG. 2

through the next two decades is that I still believe the United States to possess a great potential for new oil discoveries. You know better than I that much of our country has not yet been explored and, much better than I, that even more of it has not been covered by modern geophysical techniques. We not only continue to find new oil by intensive reworking and restudy of the older producing areas, but also by discovering and developing entirely new producing regions. This has long been the pattern but is sometimes overlooked by those who seem to conclude that most of our future new oil must be expected to come from the already producing areas. A recent and excellent example of the shifting pattern of discovery and production is the Paradox Basin near the Four Corners of Arizona, Utah, Colorado, and New Mexico. Only slightly less recent is the sensational success

rate of the Gulf of Mexico Continental Shelf area, where the discovery of a hundred feet plus of good oil sand on a virgin dome has recently been occurring so frequently offshore from Louisiana as to become almost commonplace. When to the great potentialities of the U. S. are added the vast unexplored areas of Canada and Mexico, it would seem that the oil finding forces of the industry will not lack North American frontiers to challenge for many years to come.

But whether or not the exploration partnership of geophysicists and geologists

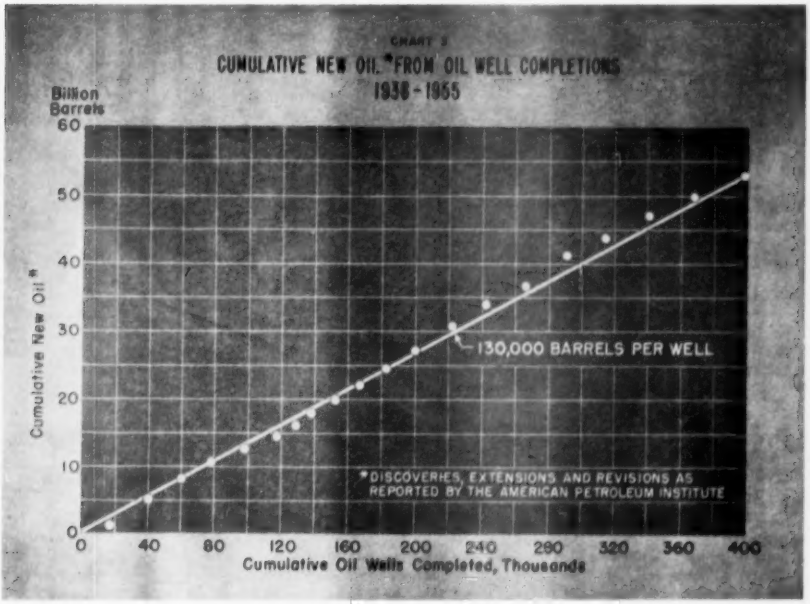

FIG. 3

will be able to meet pyramiding demands until 1965 or 1975, or thereafter, one fact seems clear. The partners must and undoubtedly will increase and intensify the search. The job to be done is a big one and it will be a costly one. I have long thought that those who reiterate that "oil is becoming harder to find" are using the wrong adjective in describing the difficulties of the present-day search. I do not believe that oil is any harder to find than it was in the thirties, but I know the cost is more than five times as much!

From the operating standpoint, those in future exploration will have two main assignments:

(1) The techniques of finding must continue to improve. This is a challenge both to the geophysicists and geologists. It will require the best efforts of all of

us. Your own activities indicate that you realize this fact and there is no letdown in this direction. I am amazed at the technical developments you have made since the war—magnetic tape, for example,—and by the potential promise shown by some of your other new approaches.

(2) The second major operating requirement is that we continue by every means possible to combat the rising costs of both exploration and production. It is conceivable that in a competitive economy with one source of energy competing with another, we could price ourselves out of business before we exhaust our physical resources.

In closing I should like to express the conviction that:

Continuing success in oil and gas exploration in this country will in the last analysis depend on intensive education and training of larger numbers of well-qualified, imaginative exploration personnel, the development of even better instruments and greater technical skills, the willingness and ability of the industry to take large calculated risks and to support in a wholehearted manner its exploration people, and, finally, a continuation of the close teamwork of *Geophysics—Geology—Full Partners*.

GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 233–260, 14 FIGS.

SOUND PROPAGATION IN COMPACTED OCEAN SEDIMENTS*

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ABSTRACT

Experiments were made in the laboratory to measure the velocity of propagation of compressional and transverse elastic waves in ocean sediments while under varying conditions of compacting pressure. Various attempts to formulate expressions relating velocity with composition are discussed and are found to be not applicable to compacted sediments. The concept of a structure bulk modulus is introduced to account for the observed velocity changes.

Shear waves were observed at compacting pressures exceeding 500 kg/sq cm. The effects of hydrostatic pressure and the development of anisotropy are also studied.

INTRODUCTION

The study of wave propagation in granular media has always been of interest to those working in the field of seismic prospecting. During the last decade seismic techniques have been developed for structural studies of the ocean floor and the problems of interpretation have been correspondingly more difficult than those on land. In particular, the seismic refraction technique used at sea working with charges and hydrophones near the surface, is insensitive to the thin and comparatively low velocity layer of unconsolidated sediments that in nearly all places covers the basement rocks. Some information can be obtained about this layer from wide angle reflections from the bottom and from layers within the sediment but the results are not conclusive (Hill, 1952, Officer, 1955). Furthermore, apart from the top fifty feet or so, the layer is inaccessible for sampling and it is therefore difficult by direct stratigraphic observation to confirm any conclusion reached.

Workers in soil mechanics have advanced far, both in the experimental and theoretical aspects of the effect of an overburden on the physical properties of buried sediments, especially in the low pressure region, and have developed laboratory methods for compaction studies. A research programme was undertaken at Cambridge in an attempt to combine the techniques of laboratory compaction experiments with ultrasonic elastic wave velocity measurements in order to derive estimates of how the velocity varies with depth of burial of sediments on the ocean floor.

This paper, in which the first part of this research is described, is concerned with the variations of velocity with changes of compaction pressure. In a later paper, these will be related to the depth of burial of the sediments and the resulting velocity profiles will be discussed.

The mechanism of elastic wave propagation in granular media has been the

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subject of many recent papers (Urick 1947, Gassman 1951, Morse 1952, Ament 1953) and these have shown how only with very simple models can expressions for the velocity and attenuation be formulated explicitly in terms of the composition of the media. In order to understand better the mechanism in real sediments, a more empirical approach has been used in which the elastic constants of an equivalent homogeneous medium are derived from the velocity observations and these are compared with the elastic constants of the constituents.

EXPERIMENTAL APPARATUS

The apparatus used in the experiments consists of two parts, one being concerned with the application and maintenance of a compacting pressure on the sample, the other being concerned with the measurement of the velocity of sound through the sample.

The pressure pot containing the sample was designed so that both measurements of compression and velocity could be carried out simultaneously. The design is shown in Figure 1, the sample diameter being 5 cm, its initial length 5 cm and its final length after compaction at 100 kg/cm^2 being about 2 cm. Water was drained from the sample through two porous discs of white bauxilite grinding wheel material backed by drainage holes through the piston and through the bottom. Quartz crystals were mounted in the piston and on the base behind steel bosses which supported the internal pressure, leaving the crystals at atmospheric pressure. These bosses protruded through the porous discs and were flush with them keeping the sample cavity cylindrical.

The pressure was applied to the pot by means of a 35-ton ship jack working directly onto the piston of the pressure pot. The jack could be operated manually and was backed by a hydraulic system of relays and a booster pump (Figs. 2 and 3). Three gauges of different ranges were connected with Bourdon gauge relays which controlled a high torque electric motor driving the pump. Taps enabled various parts of the system to be isolated at will without reducing the pressure, thus allowing the whole range of pressures from 10 to 1,000 kg/cm^2 to be measured to within a few percent on the appropriate gauges. The relay system enabled the pressure to be maintained at any fixed value within these limits.

The length of the specimen was measured by a vernier scale giving the differential movement of the piston and cylinder to an accuracy of 0.01 cm. More accurate measurements of changes of length were made by a dial gauge reading to 0.001 cm.

For some of the work it was necessary to pressurise the interstitial water in the sample while the compacting pressure was acting. This required a secondary hydraulic pressure system operating through an oil-water exchange reservoir and applied to the drainage outlets. In these experiments the piston was sealed to the cylinder with an annular *U*-washer of *PVC*. The maximum hydrostatic pressure applied in this way was 500 kg/cm^2.

VELOCITY MEASUREMENT

The electronic apparatus for the velocity measurement is shown diagramatically in Figure 4. A square wave form is generated in the pulse generator, the leading edge of which triggers the sweep of a two beam oscilloscope. The trailing edge then triggers a 2 kV single pulse of fast rise time and slow decay time which

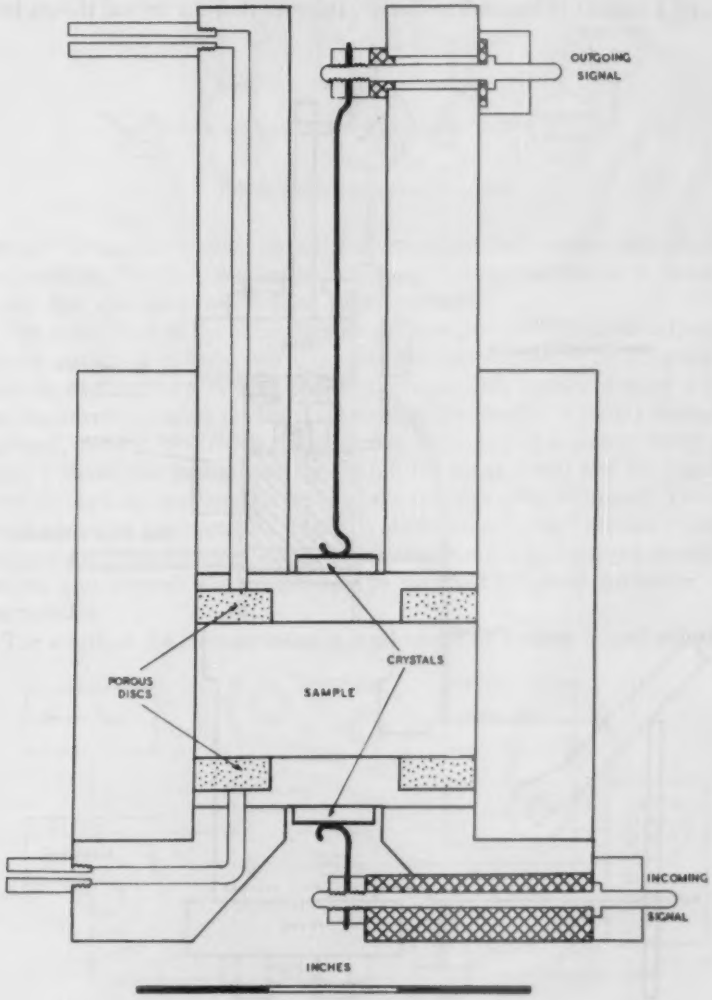

FIG. 1. Pressure pot.

is applied to the transmitting crystals of both the pressure pot and an adjustable mercury delay line. The signals received through both paths are amplified and displayed separately on the two beams of the oscilloscope. A pulse repetition rate of about 1 kc/s is used to obtain a steady picture.

X-cut quartz crystal transducers of 1 mc/s natural frequency were chosen because of their stability, small size and ruggedness. They are coupled to the steel bosses by a cement of beeswax and resin. In order that the crystal should be ef-

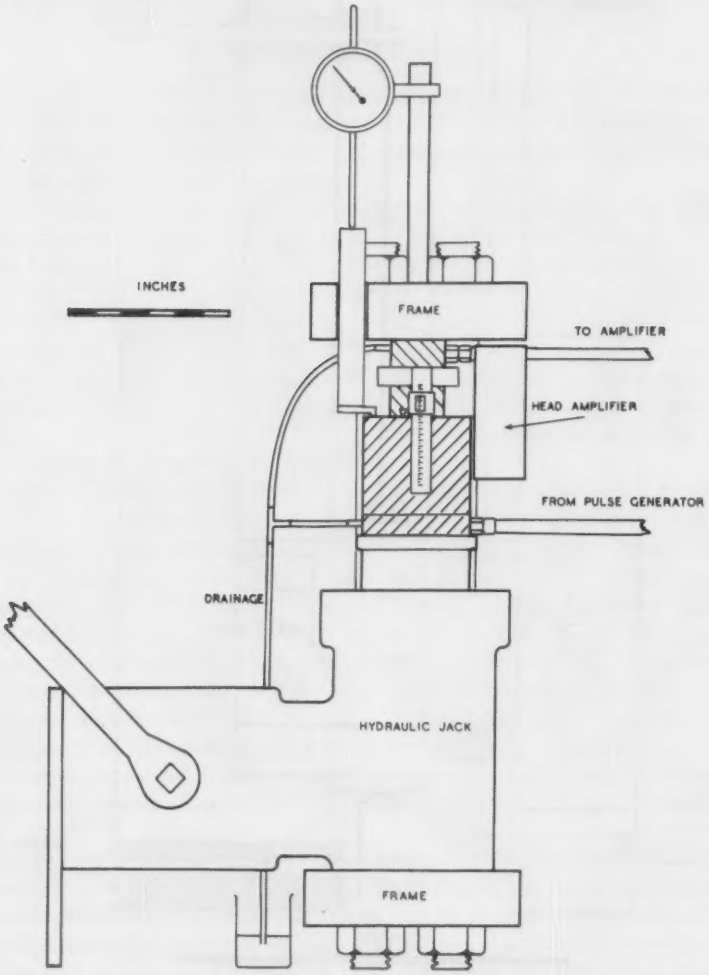

FIG. 2. Compression apparatus.

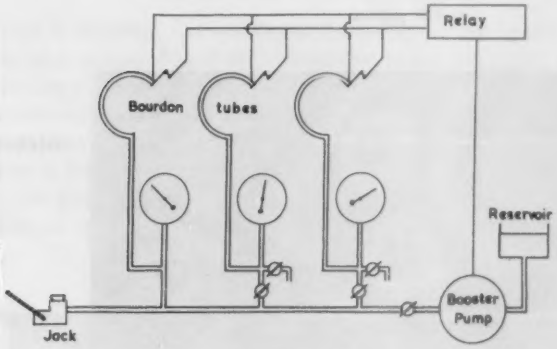

FIG. 3. Diagram of hydraulic system.

fectively air backed, contact with the silver-coated back surface is made with a wire whisker. No effort was made to prevent natural oscillation of the crystal as only first arrivals of wave trains were measured.

The travel time of the pulse through the mercury column can be adjusted by varying the length of the column, to allow the first arrivals of both signals to be superimposed on the screen of the oscilloscope. This enables a more accurate time measurement to be obtained than would be possible if timing marks were displayed, since it is difficult to judge the beginning of a slowly rising pulse. Figure 5 shows the transmitted signals (on the lower trace) and the signals received through the specimen (lower) and the mercury column (upper). The travel time is about 10 microseconds. Figure 6 shows an expanded picture (using the unsuppressed flyback sweep) and demonstrates how the first arrivals through the mercury and through the sample can be matched in initial curvature before superposition.

The length of the mercury column is measured by a screw thread adjustment

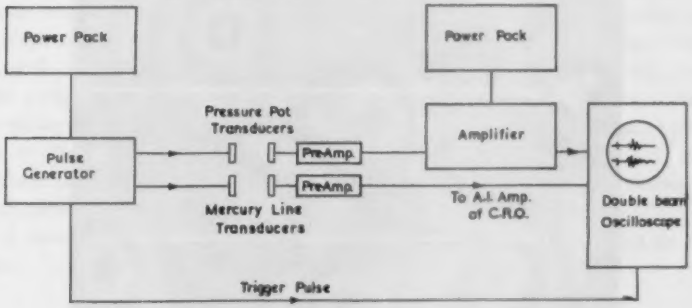

FIG. 4. Block diagram of electronic apparatus.

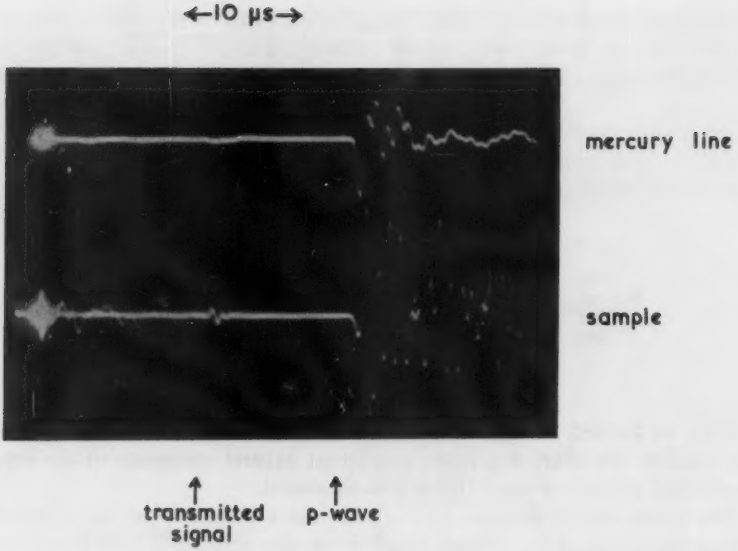

FIG. 5. *P*-wave arrivals.

calibrated in centimeters. Corrections were obtained for the various metal paths through which both pulses have to travel. The velocity of sound in mercury was taken as 1.460 km/sec at 0°C. with a temperature coefficient of −0.000465 km/sec/°C. (Hubbard and Loomis 1928). Thus knowing the length of the specimen, the equivalent length of mercury column for equal travel time and the

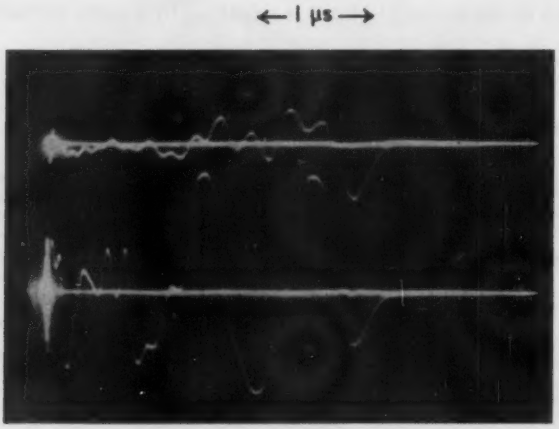

FIG. 6. *P*-wave (expanded trace).

velocity of sound in mercury, the velocity in the specimen can be calculated. For a sample 2 cm long, provided that the attenuation is not too great, an accuracy of 1 percent can be obtained.

The measurement of shear wave velocities was achieved using *Y*-cut quartz crystals. The application of an electric field in the *Y* direction across such a crystal produces a lateral elongation or contraction parallel to the *X* crystallographic axis, thus giving rise to transverse waves in the *Y* direction. The piezoelectric modulus of quartz for this propagation is the same as that for com-

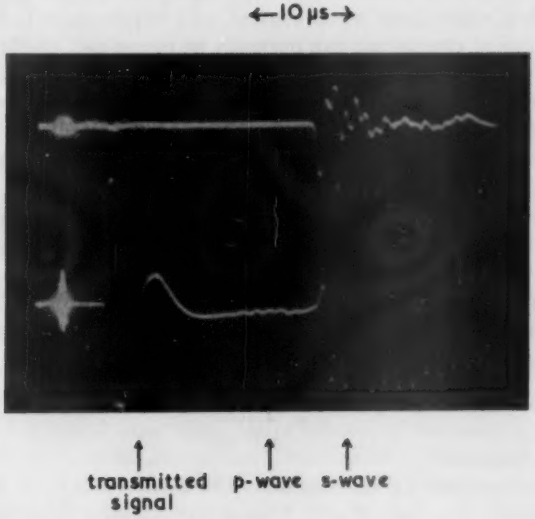

FIG. 7. *P*- and *S*-wave arrivals.

pressional wave propagation with *X*-cut crystals. Thus the energy propagated in the shear waves should be approximately the same as in compressional waves apart from acoustic mismatching and coupling difficulties. Preliminary experiments with *Y*-crystals waxed onto metal and rock specimens showed that in fact the energy propagated in shear waves was greater than that propagated in compressional waves under similar circumstances. A small proportion of the energy, however, is converted into compressional waves at the boundary, giving measurable signals arriving before the slower shear waves. Figure 7 shows both *P* and *S* wave arrivals through a specimen of carboniferous limestone. Thus both *P* and *S* wave velocities may be measured without changing from *Y*-cut to *X*-cut crystals.

EXPERIMENTAL PROCEDURE

The procedure used for the experimental examination of the compaction of sediments has been developed and standardised by workers in soil mechanics (Terzaghi 1925; Taylor 1942; Skempton 1944). Although the range of pressures

studied here is considerably larger than that met with in soil mechanical studies, the same procedure was used so that results should be comparable. Increments of pressure were applied logarithmically thus enabling the early stages of compaction, where the density changes rapidly with pressure, to be studied in as great detail as the later stages. In most experiments the pressure was increased by a factor of two for each increment.

The time for which each new pressure was applied depended to a large extent on the nature of the sample being consolidated. A coarse-grained sandy sample will attain an equilibrium value of compaction in a few minutes while a fine-grained clay with a large water content may require days to reach equilibrium. Two stages of compaction can normally be recognized, the first being governed by the viscosity of the interstitial water, escaping through a more or less permeable medium, the second and slower process being connected with the plastic flow of an adsorbed water film between points of contact of grains. The first stage is comparatively quick but the second stage may continue for months or even years. Since the expulsion of free interstitial water results in the greater part of the volume change, the time for which any one pressure was applied was chosen to cover complete primary consolidation. This varied from one hour to one day.

From measurements of initial and final mass and from the volumes of the specimen while under pressure, the density ρ at any pressure can be calculated and hence also the void ratio using the relation

$$\epsilon = \frac{\rho_s - \rho}{\rho - \rho_w}$$

where ρ_s = density of solid grains and ρ_w = density of water.

DESCRIPTION OF SAMPLES

The samples used in this work were obtained principally from cores taken during 1952 by R.R.S. "Discovery II" in the north-eastern Atlantic basin. These are listed in Table I, which gives the physical properties in their uncompacted state. Where available, grain density measurements are quoted. However, since the accuracy of these measurements is not better than a few percent, a constant value of $\rho_s = 2.69$ gms/cc was used throughout in calculations of void ratio.

Cores 2994 and 2995 are globigerina ooze whereas the remainder, which are nearer to the continental shelf edge, can be termed terrigenous muds since their carbonate content does not exceed 30 percent. The cores, the maximum length of which was 2 m, showed marked variations in color with depth, associated with changes of sedimentary conditions. The samples used in the compaction experiments were taken from two contrasting material types, represented by core 2994 and core 2992. Within each type the samples used for each experiment were chosen to be as similar as possible.

TABLE I

PHYSICAL PROPERTIES OF THE UNCOMPACTED SEDIMENTS

Station No.	Position	Depth, fms.	Mean density, gms/cc	Percent $CaCO_3$ ‡	Mean grain density gms/cc	Liquid limit †	Plastic limit †	v_P, km/sec
2992	49°48′N 12°28′W	1,140	1.61 ± .03 (8)	21.0 (3)	2.71 (3)	56	24	1.51 (2)
2993	49°58′N 18°33′W	2,105	1.62 ± .06 (6)	26.5 (4)	2.69 (1)	—	—	1.54 (2)
2994	49°08′N 17°37′W	2,577	1.62 ± .01 (16)	54.0 (1)	2.69 (2)	61	23	1.63$_8$ ± .01 (14)
2995	48°14.5′N 16°47′W	2,553	1.55 (2)	53.8 (1)	2.73 (1)	—	—	1.54 (1)
2996	48°52′N 15°00′W	2,577	1.54 ± .01 (5)	17.3 (1)	—	—	—	1.47 (1)
2997	49°26′N 12°49′W	781	1.67 ± .03 (7)	26.2 (1)	—	—	—	1.500 ± .005 (12)

† water content measured in gms. water per 100 gms. dry solid.
‡ $CaCO_3$ content measured in gms. $CaCO_3$ per 100 gms. dry solid.
N.B. All errors quoted are standard deviations of the mean.
The figures in parentheses denote the number of independent measurements.

The Atterberg limits quoted in Table I give a measure of the consistency of the samples. The liquid limit is the water content of the sample when enough water is added for it to behave on the borderline of a plastic and a liquid. The plastic limit is the water content when enough water is removed for it to behave on the borderline of a plastic and a solid. The limits were determined by the standard methods described by Casagrande (1932), and are largely empirical. They are useful however in comparing different soils.

The grain size distribution of these core types has been given by Bramlette and Bradley (1941) and Revelle (1944), for similar sediments from the Atlantic and the Pacific. Globigerina ooze shows two broad peaks in the size distribution corresponding to foraminiferal test size (100 microns) and lutite fraction (2 microns). The two components are present in approximately equal quantities and give rise to a somewhat gritty texture. Terrigenous mud consists principally of lutite and is smooth and slimy to the touch.

The lutite fraction comprises the clay minerals which are of colloidal size and generally plate-like in shape. The property of these mineral grains to surround themselves with a semicrystalline layer of adsorbed water and to acquire electrical charges is responsible for the unusual bulk properties of clays and their action with change of water content. These adsorbed water layers appear to play a big part in the propagation of sound through the material.

VELOCITY IN UNCOMPACTED MATERIAL

The P wave velocities measured in uncompacted samples are listed in Table I. A comparison of these measurements with the carbonate content suggests that the more calcareous the sediment, the higher the velocity. This however, is probably a secondary effect, the basic relation being between the grain size and the velocity. No correlation of velocity with depth of burial could be observed over a depth of 2 m. The top few centimeters of the core which generally appeared to be very sloppy were, however, badly disturbed during coring, and thus no measurements were made in this range.

No S waves could be measured in the uncompacted material. This is not surprising in view of its very low rigidity.

VELOCITY CHANGES WITH COMPACTION

The velocity of P waves at each equilibrium state in all the experiments carried out on samples from cores 2994, 2992 and a sample of Pacific red clay is plotted in Figure 8 against the square root of the compacting pressure. Small differences in the uncompacted velocity of different samples within one group account largely for the scatter of points at the lower pressures. The remaining scatter is due to the slightly varying conditions of compaction, such as the pres-

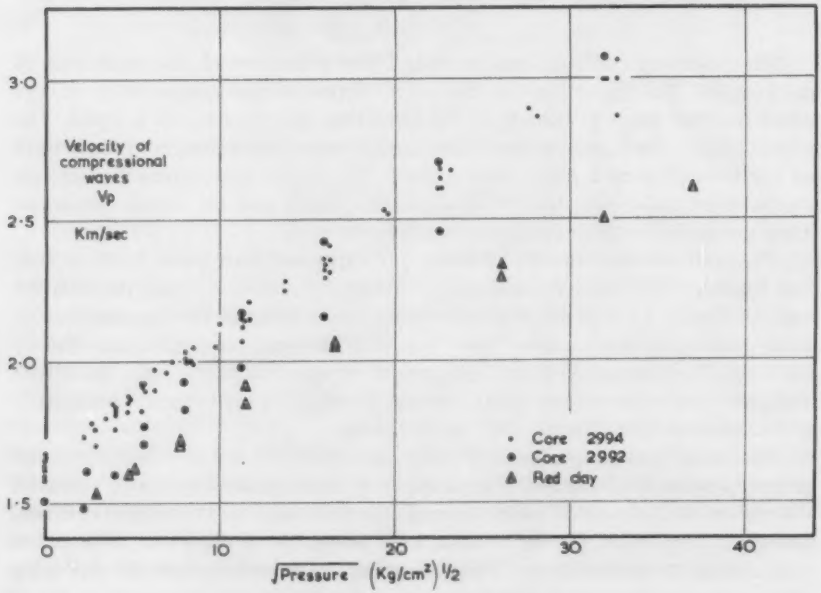

FIG. 8. Summary of velocity-pressure relations for all experiments.

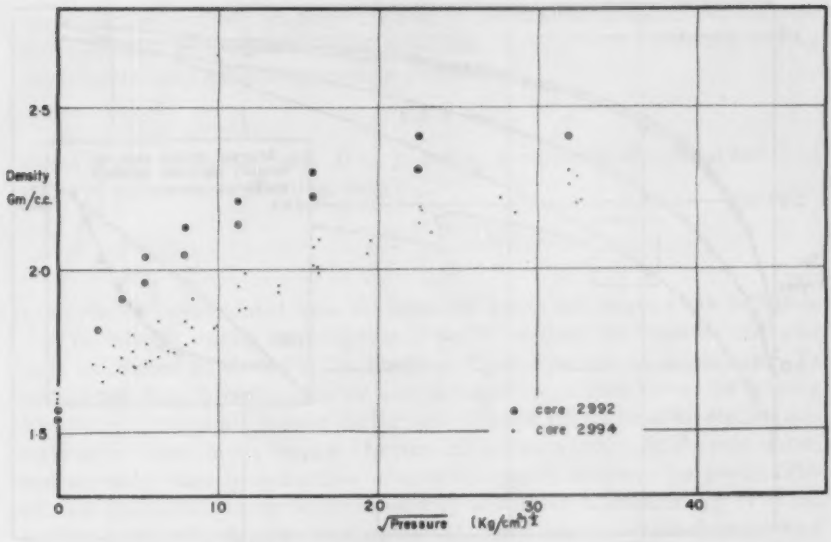

FIG. 9. Summary of density measurements as a function of pressure.

sure increment ratio, and the time for which the pressure is applied.

The terrigenous and red clay sediments have lower initial velocities than the calcareous sediments. The maximum velocity attained by the red clay samples was significantly lower than that of the other materials. Figure 9 shows the effect of compression on the density in the same samples (excluding the red clay) and corresponds point for point with Figure 8. A comparison of the clays with the oozes shows that in spite of the more rapid increase of density with pressure in the clays, the velocity increase is not appreciably greater. No density measurements during compression of the red clays are available.

It is instructive to study one curve, obtained from experiment (4) on a sample from core 2994, where detailed measurements were made of velocity changes on compression and decompression followed by another cycle of compression and decompression. The pressure increment ratio was $\sqrt{2}$. In Figure 10 the P wave velocity is plotted against the pressure and in Figure 11, against the void ratio. The change in void ratio of the sample over the whole range of compression is from 1.78 to 0.40 whereas the increase during decompression is only from 0.40 to 0.47; i.e. 5 percent of the original decrease. This small change must be compared with the change of velocity during decompression which is 79 percent of the total increase during compression. It can be inferred from this fact that the velocity is a function not only of the ratio of solid to liquid in the specimen but also of the intergranular pressure. Neither pressure nor void ratio alone can account for the velocity changes.

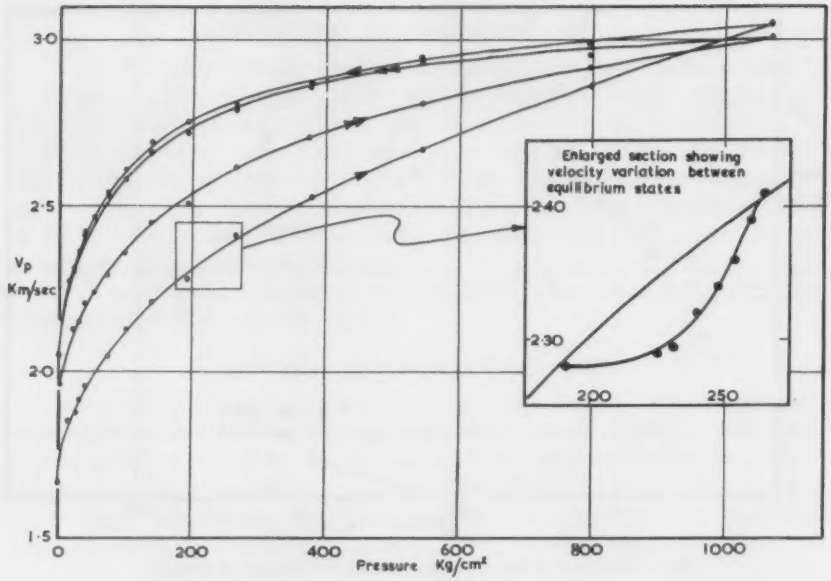

FIG. 10. Velocity-pressure relation for experiment 4.

Subsequent recompression and decompression show that the velocity follows a hysteresis cycle that is approximately repeatable. Two possible factors might have been responsible for the hysteresis. The first was the friction of the piston and the sample in the pressure pot. This alone, however, would require frictional forces equivalent to about 40 percent of the applied pressure; subsequent measurements of this friction show that it did not exceed 15 percent after the first compression.

The hysteresis may, secondly, be due to an internal effect caused by the plastic nature of deformation of the grain structure. The force tending to push the particles together during compression is that applied externally and it is resisted by both the elastic restoring forces and plastic deformation forces which arise from the colloidal nature of the sediment and the envelopes of adsorbed water on the grains. When the pressure is released, the particles are forced apart by the elastic forces but their relative motion is again resisted by the plastic forces, giving rise to the hysteresis effect.

Velocity measurements were also made while the sample was still compacting. The effective pressure (defined as the total interparticle force per unit area of cross section of the sample) at any stage in the consolidation process may be calculated using the assumption, made by Terzaghi in his theory of consolidation (Terzaghi 1943) that the void ratio change during compaction is determined solely by the

excess pore water pressure. Since the sum of the effective pressure and the pore water pressure is constant during compaction, the void ratio ϵ is determined by the instantaneous effective pressure p such that

$$\epsilon + k_1 p = k_2$$

where k_1 and k_2 are constants. If ϵ_1, p_1 and ϵ_2, p_2 represent the initial and final states of a pressure application, then

$$\frac{p - p_1}{p_2 - p_1} = \frac{\epsilon_1 - \epsilon}{\epsilon_1 - \epsilon_2}.$$

ϵ can readily be calculated from the specimen length and hence p can be found.

The velocity during consolidation is plotted against the pressure and void ratio calculated as above, in the insets of Figures 10 and 11 respectively. In neither case does the curve coincide with the equilibrium state curve, the velocity always being too small. A state during consolidation differs from an equilibrium state in two ways: firstly there is a hydrostatic pressure present in the pore water, and secondly there is continuous relative movement between the grains. The effect of hydrostatic pressure on the velocity was shown experimentally to be too small to account for this (see later) and so it is likely that the equilibrium velocity

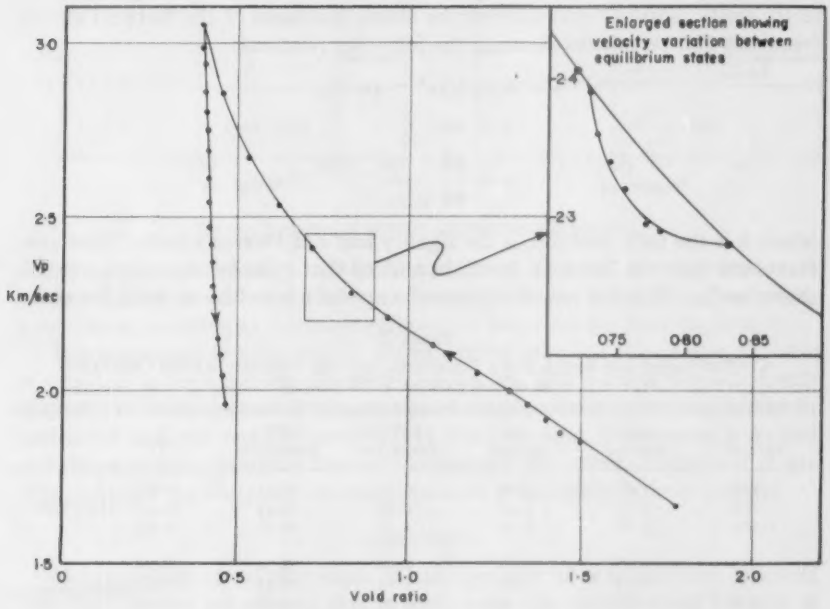

FIG. 11. Velocity-void ratio relation for experiment 4.

is reached only when the relative movement of particles has ceased. This is consistent with the theory that the velocity increase is due principally to the establishment of a particle structure. While relative movement is taking place, the particles will tend to surround themselves with adsorbed layers of water which will not be removed until secondary compression takes place and the layers are squeezed from between the solid particles.

SHEAR WAVE VELOCITIES

Shear wave arrivals were looked for in the compaction experiments on both ooze and mud samples, but could only be found in the ooze at high degrees of consolidation. Because of the conversion of S to P waves at the generating crystal, simultaneous measurements of both velocities were made when the S waves could be positively identified in the P wave train. At maximum pressure the S wave amplitude was about six times that of the P wave. On decompressing, the relative amplitude of the S wave fell until it was lost in the P wave train below 64 kg/cm². Once identified, the S wave arrival could be followed into the lower amplitude range with more certainty.

Table II gives the S and P velocities on a sample from core 2994 during the last stages of compression and during decompression. From these velocities v_P and v_S and the density ρ and (assuming the mixture to behave as a homogeneous perfectly elastic isotropic material) all the elastic constants of the material at this frequency can be calculated, using the following relations

$$k = \rho(v_P^2 - 4v_S^2/3)$$

$$\mu = \rho v_S^2$$

$$\sigma = \frac{3k - 2\mu}{6k + 2\mu}$$

where k is the bulk modulus, μ the rigidity and σ is Poisson's ratio. These constants are shown in Table II. It will be noticed that σ lies between 0.50, which is the value for a liquid of zero rigidity, and 0.25 which is a common value for rocks.

TABLE II

COMPRESSIONAL AND SHEAR WAVE VELOCITIES, AND THE DERIVED ELASTIC CONSTANTS
Sample of glob. oz. (CORE 2994)

p kg/cm²	v_P km/sec	v_S km/sec	10^{-11} k dynes/cm²	10^{-11} μ dynes/cm²	σ	
512	2.68	1.20	1.13	0.31	0.37	Compression
768	2.89	1.42	1.25	0.45	0.34	
1,024	3.06	1.57	1.38	0.56	0.32	
512	2.98	1.51	1.32	0.51	0.33	Decompression
256	2.77	1.40	1.14	0.44	0.33	
128	2.63	1.30	1.12	0.36	0.35	
64	2.48	1.22	0.93	0.33	0.34	

THE EFFECT OF HYDROSTATIC PRESSURE ON THE VELOCITY

In order to investigate the effect on the velocity of removing the sediment samples from the sea bottom to atmospheric pressure, hydrostatic pressure was applied to the drainage water at each equilibrium stage of compaction. The effect of these pressure changes on the P wave velocity is illustrated in Figure 12 for samples from cores 2992 and 2994. Included for comparison is the variation of velocity with pressure in sea water; 400 kg/cm² is equivalent to about 4 km.

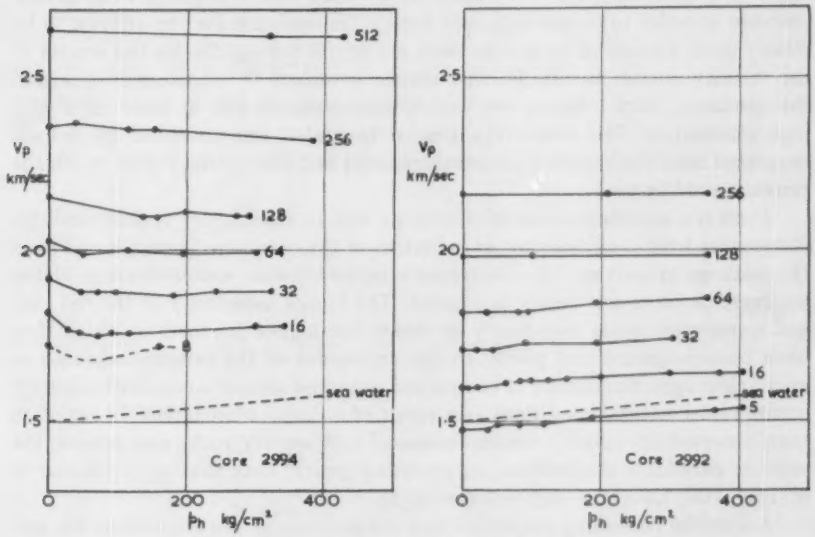

FIG. 12. Variation of velocity with hydrostatic pressure.

In no case does the velocity change by more than 3 percent for this pressure. A marked difference can be seen between the results for the two different materials, a minimum occurring at the lower compaction pressures for the ooze sample.

It is interesting to note that the increase in velocity at a compaction pressure of 5 kg/cm² is the same for clay as for sea water. This increase is reduced with reduction of water content. The reduction of velocity for the ooze sample may be associated with the relative movement of particles when the pressure is applied and the consequent breaking down of interparticle structures. At the later stages of compaction the effect of hydrostatic pressure is negligible for both samples.

ANISOTROPY

Measurements of velocity made on the specimen after it had been removed from the pressure pot showed that in some cases the velocity along the axis of compaction differed from that perpendicular to it by as much as 30 percent. Table

III lists the measurements made and expresses the anisotropy as the ratio of the P wave velocity in a transverse direction to that in a longitudinal direction. The maximum pressure to which the samples have previously been submitted is also listed.

The samples were cut roughly to a cube and measurements of v_P, v_{SV} and v_{SH} were made in three directions at right angles. (v_{SV} is the velocity of shear waves polarised parallel to the axis; v_{SH} that of waves polarised perpendicular to the axis.) The measurements were made in a clamp which required considerable pressure in order to obtain sufficient energy transmission for the arrivals to be clearly seen. Variations in this pressure are partly responsible for the scatter of the velocity measurements. Further scatter is caused by inhomogeneity within the specimen, partial drying out during measurements and in some cases very high attenuation. The mean velocities are tabulated and the errors quoted are estimated from the variations in measurements and the accuracy with which the arrivals could be read.

There is a notable increase in anisotropy with increasing clay content and this is apparent from a microscopic examination of the compacted samples and from the cleavage properties. The calcareous samples show no visible cleavage planes whereas the clays are clearly laminated. The higher anisotropy of the red clay and terrigenous muds may partly be due to the higher pressures to which they have been subjected and partly to the drying-out of the samples resulting in micro-cleavages. Anisotropy in compacted clays and similar laminated sediments occurs under natural conditions as a result of uniaxial compaction. It has often been observed in velocity measurements of sedimentary rocks and schists, the velocity parallel to the bedding always being greater than that perpendicular to it (Day, Hill, Laughton and Swallow 1956).

A material possessing properties that are isotropic in two dimensions but anisotropic with respect to the third is called transversely isotropic. The elastic behavior of such a material can be described in terms of five elastic constants, A, C, F, N and L (using the notation of Love's "Elasticity"), instead of the usual two for isotropic media. The velocities of elastic wave propagation in a transversely isotropic medium have been derived by Stoneley (1949).

Let us assume that the axis of symmetry is in the z-direction. Then for the propagation in the z-direction

$$v_P = (C/\rho)^{1/2}$$
$$v_S = (L/\rho)^{1/2}$$

For propagation in the x- or y-directions

$$v_P = (A/\rho)^{1/2}$$
$$v_{SV} = (L/\rho)^{1/2} \quad \text{(polarisation parallel to } z\text{-direction)}$$
$$v_{SH} = (N/\rho)^{1/2} \quad \text{(polarisation perpendicular to } z\text{-direction)}$$

TABLE III

ANISOTROPY IN COMPACTED SEDIMENTS

Sample	Maximum pressure kg/sq cm	Velocities					v_P(trans) / v_P(long)
		Longitudinal		Transverse			
		v_P km/sec	v_S km/sec	v_P km/sec	v_{SH} km/sec	v_{SV} km/sec	
Glob. oz. (2994) (wet)	256	1.77		1.89			
		1.82		1.98			
		1.88		1.94			
		1.89		1.89			
		1.91		1.95			
				2.00			
	Mean =	1.85		1.94			1.05 ± .05
Slurried glob. oz. (2994) (wet)	256	1.73		1.77			
				1.90			
		1.81		1.85			
		1.91		1.94			
				1.89			
				1.86			
				1.85			
				1.86			
		1.74		1.87			
		1.87		1.89			
	Mean =	1.81		1.87			1.03 ± .05
Slurried glob. oz. (2994) (dry)	256	1.52		1.76			1.15
Terr. mud. (2992) (wet)	256	1.88		2.08			
				2.12			
				2.14			
		1.88		2.11			
		1.88		2.12			
				2.20			
	Mean =	1.88		2.13			1.13 ± .03
Terr. mud. (2992) (dry)	256	1.58		2.26			1.43
Red clay (dry)	1,360	1.61	1.11	2.18			
				2.18			
		1.62	1.11	2.20	1.37	1.14	
				2.12	1.38		
	Mean =	1.61₅	1.11	2.17	1.37₅	1.14	1.34 ± .03
Terr. mud (2992) (partially dry)	1,024	1.95	1.29	2.65		1.34	
				2.65	1.63		
				2.65		1.24	
				2.65	1.64		
	Mean =	1.95	1.29	2.65	1.63₅	1.29	1.36 ± .03
Terr. mud (2993) (dry)	850	1.59		1.90			
				1.98			
				1.95			
	Mean =	1.59		1.94			1.22 ± .05

The fifth elastic constant F is only involved in the propagation of P and S waves in directions not parallel to a principal axis. It was therefore not possible from the observations made, to calculate this constant. For an isotropic material the constants reduce to

$$A = C = \lambda + 2\mu$$

$$F = \lambda$$

$$L = N = \mu$$

λ and μ being the Lamé parameters.

It will be noticed that v_S in the z-direction is equal to v_{SV} in the x- or y-direction. This is verified by the experimental results in Table III for the red clay and terrigenous mud. It follows from the measured velocities that $L<N$. This is to be expected since

$$L = \mu_{zz} = \mu_{zx} = \mu_{yz} = \mu_{xy}$$

and

$$N = \mu_{xy} = \mu_{yx}$$

where μ_{ij} are the rigidity moduli measured by application of a stress on the ith face in the jth direction. L corresponds to a strain involving the parallel displacement of the laminae whereas N corresponds to a strain in the plane of the laminae. The measurements show that where anisotropy exists $A>C$.

If the sediments on the ocean floor show transverse isotropy then the interpretation of seismic velocities in this layer and the corrections to be applied to rays travelling to lower layers must be adjusted to take this into account.

THE THEORY OF WAVE PROPAGATION IN TWO COMPONENT SYSTEMS

Various attempts have been made to derive an expression for the velocity and attenuation of elastic wave propagation through a medium consisting of a mixture of two components, either both fluid or one fluid and the other solid, in terms of the elastic moduli, densities and relative concentrations of the components. The problem is so difficult in the general case of naturally occurring mixtures such as gravels or clays where there is a complicated interaction between particles that considerable simplifying assumptions have to be made before it can be formulated mathematically and these assumptions are often such that the usefulness of the result is very limited.

Urick (1947) derived a simple expression for the mean compressibility and mean density of a suspension of one fluid in another on the assumption that to waves of wavelength considerably greater than the particle size, the mixture behaved as a homogeneous medium with properties intermediate between the two components. The wave velocity derived from these mean properties agreed rea-

sonably well with that measured in various emulsions and suspensions of differing concentrations.

Later a more refined theory was developed (Urick and Ament 1949) which treated the particles as scattering points and took into account the relative movement between particles and fluid in the velocity field of the sound wave and could thus provide an expression for attenuation as well as one for velocity. This "first order theory" reduces to the "homogeneous" theory for particles infinitely small. The theory assumes, however, that the scatterers are free to move and do not interact in any way with other scatterers, thus limiting its use to comparatively dilute suspensions.

A different approach was used by Gassman (1951) who started with a model of uniform spheres hexagonally close packed and deformed at the points of contact under the stress of an overburden and calculated the elastic moduli of such a system. He obtained an expression for a velocity increase proportional to the sixth root of the depth of burial. This theory was further developed by White and Sengbush (1953) who measured such an increase of velocity in natural sand beds and found the predicted effect on crossing the water table. The good agreement found was due largely to the uniform size of the sand grains and lack of clay materials in the interstices. The theory assumes that on the passage of an elastic wave there is no relative motion between solid and liquid and does not therefore give an expression for attenuation.

At the other extreme, Morse (1952) considered a model in which the particles did not move at all, the sound waves being propagated through the fluid in the interstices. This model is only valid if the fluid viscosity is very small, such as, for instance, in an air saturated sand. The velocity obtained is always lower than that in the fluid alone.

Ament (1953) approached the problem in yet another way. He assumed that one could derive expressions for the effective bulk modulus k_ω and effective density ρ_ω in the relation $v_{P\omega}=(k_\omega/\rho_\omega)^{1/2}$ that would include the effects of relative motion particles and solid. ($v_{P\omega}$ is the velocity of propagation of compressional waves for an angular frequency ω.) These expressions would be complex, the real part of $v_{P\omega}$ giving a velocity and the imaginary part giving an attenuation factor. He assumes as a first approximation that k_ω is represented simply as a weighted mean of the moduli k_i of the components. Thus

$$1/k_\omega = \sum (f_i/k_i)$$

where f_i is the fractional volume of the ith component.

By considering a hypothetical experiment in which the mixture is confined by two planes and oscillated in a direction normal to the planes, he derives an expression for the effective density ρ_ω in terms of the static density ρ_S, the component densities (solid density ρ_1 and fluid density ρ_2 for the case of a two component system), the component volume fractions ρ_1 and ρ_2 and the angular frequency ω. In his expression

$$\rho_\omega = \rho_S + \frac{i\omega H f_1^2 f_2(\rho_1 - \rho_2)^2}{f_2 - i\omega H f_1(\rho_2 + f_2(\rho_1 - \rho_2))} \tag{1}$$

the factor H expresses the permeability of the solid structure to the fluid and is defined by the relation $V = H(dp/dx)$ where V is the volume of fluid flowing through the structure in unit time per unit area normal to the pressure gradient dp/dx.

Combining the expressions for the effective modulus and density and forming the real part we find the velocity of compressional waves given by

$$v_{P\omega} = v_P\left(1 + \frac{\omega^2 H^2 f_1^2(\rho_1 - \rho_2)^2(f_1\rho_2 + f_2\rho_1)}{2\rho_S f_2}\right) \tag{2}$$

neglecting second order terms, where v_P is the velocity calculated using a static value of the density.

To estimate the order of magnitude of this effect in the frequency range that has been investigated (i.e. from zero to 1 mc/s) we require a value for H. Using Stokes law for the flow of water past spheres, one can calculate that for a suspension of isolated spheres,

$$H = 2f_2 r^2/q\eta f_1 \tag{3}$$

where r is the radius of the spheres and η the viscosity of the fluid. Officer (1955) has made use of this calculation and concludes that with certain bottom conditions at sea there is sufficient dispersion to be observed by seismic reflection techniques. The frequency range here observed is between 80 and 3,000 c/s. The value of H used by Officer based on a radius of 5×10^{-4} cm, was 2.0×10^{-6} cm^2 sec/gm.

Now in laboratory consolidation tests, the speed of compaction is related to the permeability of the sample. For linear drainage the fractional consolidation U after time t of a layer of thickness $2l$ confined between porous media is given by

$$U = 1 - \sum_{m=0}^{\infty} \frac{2\pi^2}{(2m+1)^2} e^{-(2m+1/\pi)^2 c t/l}$$

(cf. Terzaghi 1943), where m is an integer and c is the coefficient of consolidation expressing the permeability properties or the sample. c is related to H by the expression,

$$H = \frac{c\left(\frac{\Delta\epsilon}{\Delta p}\right)\rho_2}{1 + \epsilon_a}$$

(cf. Taylor 1942). $\Delta\epsilon/\Delta p$ is the coefficient of primary compressibility relating the change of void ratio with the change of compacting pressure and ϵ_a is the average void ratio during the increment.

For globigerina ooze consolidated under a pressure of 16 kg/cm², H was found to be 4×10^{-10} c.g.s. At 265 kg/cm² it had reduced to 5×10^{-12} c.g.s. A terrigenous mud gave a value of 5×10^{-13} c.g.s. under a consolidation pressure of 32 kg/cm². These values defined the range that was found and it will be seen that they are several orders of magnitude smaller than that used by Officer. The reasons for these low values are probably twofold. Firstly the channel size in a sediment of widely different grain sizes is determined principally by the smaller grains which pack the interstices of the larger ones. Thus the grain size appropriate for use in the expression for H (equation 3) should be about 1 micron corresponding to a typical clay size particle rather than 5 microns as used by Officer. Secondly, for grains of this size a certain proportion of the interstitial water is under the influence of electrostatic forces from adsorbed ions on the particles and becomes partially bound to the particles in the form of adsorbed layers. These may form a continuous sponge-like network throughout the material and will have a considerable influence on both the effective channel size and on the viscosity of the water.

Using a value of $H=5\times10^{-10}$ c.g.s. in Ament's equation (equation 2) and values of $\rho_1=2.5$ gm/c.c., $\rho_2=1.0$ gm/c.c., and $f_1=25$ percent, we get

$$v_{P\omega} = v_P(1 + 4 \times 10^{-19}F^2)$$

where F is the frequency. Hence in order to observe a 10 percent change in velocity due to frequency, we require F to be 500 mc/s. It is apparent therefore that with the materials under examination we may neglect the difference between the effective and static values of density.

THE STRUCTURE BULK MODULUS CONCEPT

The results obtained above from consideration of the effective density suggest that one is justified to a first approximation to treat the mixture as a homogeneous medium with elastic moduli and density representable by real numbers. It is necessary now to examine the elastic moduli and to consider the justification of using the equation

$$1/k = \sum (f_i/k_i) \tag{4}$$

for the bulk modulus.

In the general case, the velocity of compressional wave propagation through a homogeneous isotropic material is given by

$$v_P = [(k + 4/3\mu)/\rho]^{1/2}. \tag{5}$$

A mixture of solid and liquid may behave like a liquid in which case we can neglect μ, or it may behave like a solid in which case μ may have an appreciable value. If some globigerina ooze is sedimented in a tube, the sediment layer is quite liquid and μ may be neglected. But on the ocean bed where the sediment has lain for

millions of years and has been subjected to ever increasing consolidation pressures, its rigidity steadily increases. It is impossible *a priori* from a knowledge of the composition and condition of the sediment to put a value to the rigidity modulus since we know very little about the forces binding a compacted sediment together, but if we can estimate the bulk modulus k in equation (5) and measure v_P and ρ we can calculate μ. From a knowledge then of k and μ, all elastic constants can be calculated including Poisson's ratio. From independent measurements of Poisson's ratio in other similar materials we know the range of values to expect and can use this knowledge to decide whether the original estimates of the bulk modulus were reasonable. Furthermore at the higher stages of compaction we have some direct measurements of the elastic constants from observations of shear waves.

As a first estimate of the bulk modulus, the equation

$$k_m = k_1 k_2(1 + \epsilon)/(k_2 + \epsilon k_1) \tag{6}$$

was used, obtained from equation (4) for a two component system, ϵ being the ratio of the volume of component 2 to the volume of component 1. A value of $k_1 = 3 \times 10^{11}$ dynes/sq cm corresponding to the solid component and $k_2 = 0.22 \times 10^{11}$ dynes/sq cm corresponding to the liquid component gave the values of k_m shown in Table IV, column (5) for the void ratios given. Columns (6) and (7) give the derived elastic constants obtained from equation (5) using the experimentally determined values of velocity and density for a globigerina ooze sample.

It will be seen that the values of Poisson's ratio fall well below the expected range at the higher pressures and that it is likely that the rigidity moduli derived are too high. This implies that the bulk modulus given by equation (6) is too low by nearly a factor of two. This cannot be attributed to uncertainties in the values of k_1 and k_2 used since the expression is most sensitive to changes in k_2 which is the best known of the two moduli.

An extra factor must be added to the bulk modulus to allow for the resistance to deformation of the structure of the solid particles which plays an increasingly important part as compaction proceeds. One may consider the problem of a unit cube containing a fraction f_1 (by volume) of particles of compressibility β_1 and a fraction f_2 of liquid of compressibility β_2. A mean pressure p is applied to each face of the cube in such a way that the cube faces remain flat. We require to know the volume change of the cube.

There are two special cases which may be considered first and which will be the degenerate cases of a general expression.

(1) If the particles are not in contact, then the hydrostatic pressure $p_h = p$ acts on both particles and fluid and the compressibility of the whole is

$$\beta = f_1\beta_1 + f_2\beta_2$$

as before.

(2) If the particles are in contact and the fluid is infinitely compressible, then

TABLE IV

ELASTIC CONSTANTS DERIVED FROM VELOCITY DATA ACCORDING TO DIFFERENT THEORIES

(a) Sample 2994. Globigerina ooze. ($CaCO_3$ 54 percent)
(b) Sample 2992. Terrigenous mud. ($CaCO_3$ 21 percent)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
					Derived from homogenous theory			Derived from structure bulk modulus theory				Measured from shear wave observations		
	P kg/sq cm	ϵ	ρ gms/cc	v_P km/sec	$10^{-11}\kappa_m$ dynes/sq cm	$10^{-11}\mu$ dynes/sq cm	σ	$10^{-11}\kappa_e$ dynes/sq cm	$10^{-11}(\kappa_m+\kappa_e)$ dynes/sq cm	$10^{-11}\mu$ dynes/sq cm	σ	$10^{-11}\kappa$ dynes/sq cm	$10^{-11}\mu$ dynes/sq cm	σ
(a)	0	1.90	1.59	1.62	.32	.07	.39	(.00)	(.32)	(.07)				
	8	1.63	1.65	1.78	.34	.13	.32	(.03)	(.37)	(.11)				
	16	1.52	1.68	1.82	.35	.15	.31	(.10)	(.45)	(.08)				
	24	1.45	1.70	1.87	.35	.18	.28	(.12)	(.47)	(.09)				
	32	1.40	1.72	1.89	.36	.19	.27	(.15)	(.51)	(.07)				
	48	1.30	1.75	1.96	.37	.22	.25	.20	.57	.07				
	64	1.22	1.77	2.01	.38	.25	.23	.25	.63	.07				
	96	1.01	1.82	2.05	.40	.27	.21	.34	.74	.02				
	128	0.95	1.87	2.12	.42	.31	.20	.44	.86	−.02				
	192	0.79	1.95	2.25	.46	.39	.17	.56	1.02	−.02				
	256	0.68	2.01	2.32	.49	.46	.14	.65	1.14	−.04				
	384	0.56	2.09	2.52	.54	.59	.10	.75	1.29	.03				
	512	0.49	2.14	2.68	.58	.72	.04	.82	1.40	.10	.46	1.13	.31	.37
	768	0.39	2.22	2.89	.66	.90	.03	.92	1.58	.21	.44	1.25	.45	.34
	1,024	0.35	2.26	3.06	.71	1.06	.00	.96	1.67	.34	.40	1.38	.56	.32
(b)	0	2.21	1.54	1.51	.31	.03	.45	.00	.31	.03				
	8	(1.79)	(1.62)	(1.48)	(.33)	(.02)	(.47)	.00	(.33)	(.02)				
	16	0.85	1.92	1.60	.44	.04	.44	.06	.50	−.01				
	32	0.64	2.04	1.71	.52	.05	.45	.17	.69	−.07				
	64	0.51	2.13	1.83	.57	.11	.41	.25	.82	−.07				
	128	0.40	2.21	1.98	.65	.16	.39	.33	.98	−.08				
	256	0.31	2.30	2.16	.75	.19	.39	.40	1.15	−.10				
	512	0.20	2.41	2.46	.97	.37	.33	.50	1.47	−.01				

Parentheses indicate unreliable values.

the entire stress is supported by the structure of particles and the compressibility $\beta = \beta_i$, where β_i is the compressibility obtained in the laboratory when the mixture is compacted between porous plates.

In the general case the stress will be shared by both fluid and particles. If p_c is the stress borne by the particle structure and p_h is the hydrostatic pressure in the interstitial water, then

$$p = p_c + p_h.$$

The deformation of the particle structure by p_c will result in a change of volume of the structure and thus of the voids. If we assume that structure deformation consists only of shearing strains in the particles and interparticle bonds, then the decrease in the volume of the voids will be given by $p_c\beta_c$.

But since the particles themselves are also compressible and are subjected to a hydrostatic pressure p_h, there will be an increase in the volume of voids of $p_h\beta_1 f_1$. The total decrease in void volume will therefore be $p_c\beta_c - p_h\beta_1 f_1$.

This change in volume of the voids must be equated to the change in the total volume of the fluid due to the hydrostatic pressure and we therefore get a second relation between p_c and p_h:—

$$p_c\beta_c - p_h\beta_1 f_1 = p_h\beta_2 f_2$$

or

$$p_h/p = \beta_c/(f_1\beta_1 + f_2\beta_2 + \beta_c)$$

Since the total change of volume of the cube is

$$f_1\beta_1 p_h + f_2\beta_2 p_h$$

the compressibility β is given by

$$\beta = p_h(f_1\beta_1 + f_2\beta_2)/p$$

or

$$1/\beta = 1/(f_1\beta_1 + f_2\beta_2) + 1/\beta_c \qquad (7)$$

As either β_c or β_2 tend toward infinity, the relation reduces to the two special cases mentioned above. Equation (7) may also be written

$$k = k_1k_2(1 + \epsilon)/(k_2 + \epsilon k_1) + k_c \qquad (8)$$

In the passage of an elastic wave through a mixture, the compressions and rarefactions must be reversible and so in finding a value for the structure bulk modulus it is not permissible to consider a value derived from an ordinary drained consolidation test. On the other hand, an undrained test will give the complete modulus k. It was found that if, in an equilibrium condition during a drained consolidation test, a very small reduction in applied pressure was made, the sample expanded in a reversible elastic manner (due allowance for the reversal of piston friction being made). A series of such decompression tests at the equilibrium states of compaction is shown in Figure 13, in which the effects of piston friction have not been removed. It will be seen that when the pressure is first

reduced, the sample length does not change and then from a fairly well-defined point the expansion is linear with pressure over a short range. Structure bulk moduli from these curves are plotted in Figure 14 against void ratio for samples of globigerina ooze and clay. From a smooth curve drawn through these points,

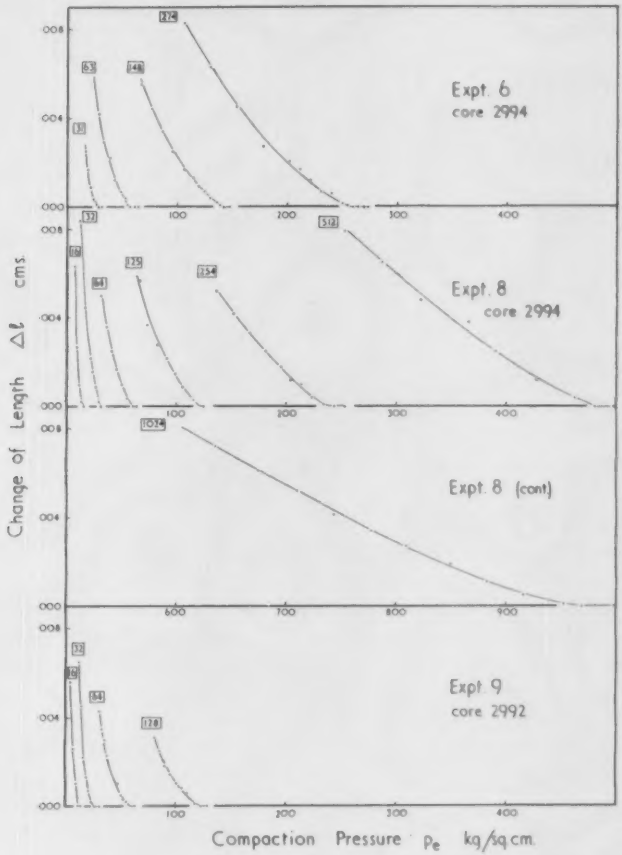

FIG. 13. Decompression curves.

values of k_c have been taken corresponding to the void ratios of the equilibrium states shown in Table IV. The first five values are not reliable since they are obtained from the extrapolation of the k_c–ϵ curve to high void ratios. The probable errors in k_c are about $\pm 0.25 \times 10^{11}$ dynes/sq cm estimated from the uncertainties of drawing a tangent to the decompression curves at zero strain, uncertainties in the allowance for volume changes of the pressure pot and from the scatter of points on the graph.

The elastic constants for the mixtures recalculated with the addition of k_c are

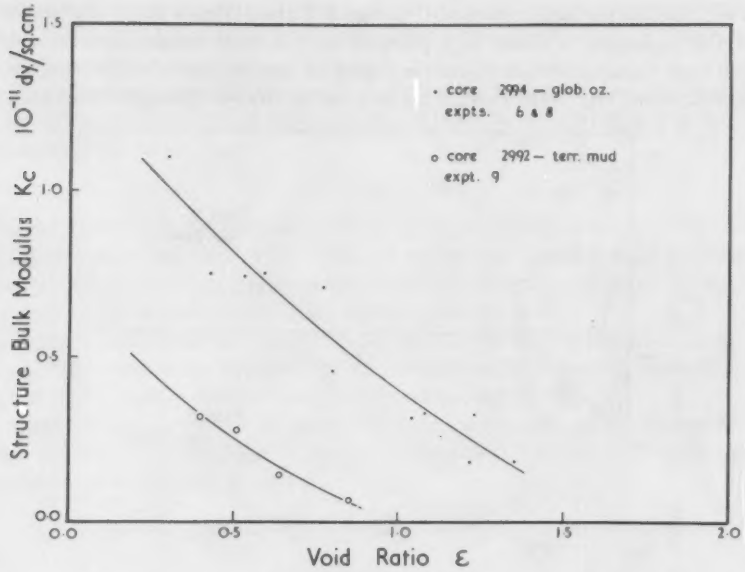

FIG. 14. Structure bulk moduli derived from decompression tests.

shown in columns (9), (10) and (11) of Table IV. The rigidity modulus, except for the highest stages of compaction in the ooze, does not differ from zero by more than the probable error. This means that the increases of velocity with increasing compaction can be accounted for in all but the most advanced stages of compaction by the increased resistance of the particle structure to compaction without having to hypothesize a rigidity. At the last two, or possibly three, stages of compaction, the rigidity begins to play an important part in the case of the ooze and this is confirmed by the fact that no shear waves were observed to be transmitted through the sample until a pressure of 512 kg/cm² was applied. For comparison, the derived values of the rigidity modulus from shear wave measurements are included in Table IV and agree in order of magnitude with those calculated. For the clay samples no shear waves were observed and a zero rigidity modulus was calculated.

CONCLUSIONS

The increase of the velocity of compressional waves with pressure in the range of ocean sediments studied can be represented approximately by the relation

$$v_P = 1.5 + 0.04p^{1/2} \qquad \begin{matrix}[v_P \text{ in km/sec.}] \\ [p \text{ in kg/sq cm}]\end{matrix}$$

up to velocities of 3.0 km/sec. There is no indication from the data that the velocity is tending towards an asymptotic value. The velocity changes can best be understood by supposing the particles of the sediment to form a structure which in part supports the stresses during the transmission of an elastic wave and which plays an increasingly important part as the compaction becomes more advanced. The structure is not strong enough, however, to sustain shear stresses at compaction pressures below about 500 kg/cm^2.

The effect of hydrostatic pressure applied to the interstitial water is shown to be negligible.

With the finer grained sediments, there is a marked tendency for a uniaxial compaction to give rise to transverse isotropy in the velocity measurements and in the physical properties. This corresponds to the first stages of the formation of slates and laminated mudstones.

Before applying these results to the buried sediments in the ocean, one must consider how the conditions of natural deposition and compaction differ from the artificial conditions used in the laboratory. The most outstanding difference lies in the different time scales of the compaction process. In the ocean, sediments accumulate at a rate of approximately 1 cm in a thousand years, or less. This corresponds to a rate of loading differing from the laboratory rate by about a factor of 10^{12}. Under these extremely slow conditions, secondary compaction may play a much more important part and there is also time for pressure induced chemical reactions to take place, such as the solution of silica from points of contact of particles and its redeposition in areas of lower stress.

Observations of the velocity of sound in sediments at sea from seismic experiments suggest that the velocity increases from a value of between 1.5 and 1.8 km/sec at the surface to over 2 km/sec at a depth of a kilometre. In seismic computations, a mean velocity of 2.0 km/sec is often used. This is consistent with the range of velocities discussed in this paper. The discontinuity below this top layer, below which the velocity jumps to a value of 4 to 5 km/sec, cannot be explained on the basis of compaction alone since the pressures available are not sufficient. If the second layer is derived from similar sedimentary material, then it must have been subjected to temperature, pressure or chemical conditions which do not prevail to-day.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 261–267, 4 FIGS.

THE STRUCTURE OF THE NOISE BACKGROUND OF A SEISMOGRAM II*

C. W. HORTON†

ABSTRACT

One second samples of two seismogram traces are analyzed statistically. The traces represent the outputs of two geophones at depths 75 and 125 feet which were part of a vertical spread. The first four moments and the first four semi-invariants and the standard deviation are computed for the first and second halves of a one second sample from each trace. These quantities are used to compute the distribution functions of the amplitudes of the seismogram traces. The resulting curves agree very closely with the distribution functions determined directly from the seismogram trace. The number of zeros per second are computed from a theoretical formula developed by Rice (1945). It is shown that the observed number of zeros per second agrees with the predicted value, but the agreement is limited by the small number of zeros that occur in a one second sample. Some general conclusions regarding the statistical behavior of the noise background of a seismogram are offered.

INTRODUCTION

Part I of this paper (Horton 1955) contained an analysis of two geophone traces which were part of a vertical spread of geophones. This analysis was based on the assumption that the noise background was due to the arrival at random times of a large number of similar individual events. Although this assumption is very plausible from physical considerations, it is desirable to test the assumption by measuring the statistical properties of the seismic traces. There are two statistical properties of a seismogram trace which are easily measured and which are suitable for testing the assumption just mentioned. These are the frequency function $f(I)$ of the amplitudes, I, of the siesmogram trace and the expected number of zeros per second of the seismogram trace.

In this paper, as in Part I, the notation of Rice (1944, 1945) will be used. However, the statistical terminology such as frequency function, etc., is based on the usage of Cramér (1946).

THE STATISTICAL ANALYSIS

Part I of this paper contained a description of some experimental records measured by Texas Instruments Inc. of Dallas. The two traces for which an analysis was carried out in Part I were labelled Case B and Case C. These traces represented outputs of geophones located at 75 feet and 125 feet, respectively. Each of these geophone traces was analyzed as follows. A zero line was drawn and the amplitude, I, of each trace was read on an arbitrary scale at intervals of 4 milliseconds. Two hundred and fifty readings were made on each trace over a one second interval extending from 0.46 to 1.46 seconds. The 500 numerical values of the amplitudes were made available to the writer in tabular form. The ordinate scale was such that 2% of the values had a magnitude in excess of 500.

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Since preliminary calculations showed that the root-mean-square amplitude of the trace decreased perceptibly during the one second sample, each sample was divided into two half-second intervals. The two half-second intervals for Case B are labelled B-1 (trace B, 0.46 to 0.96 second) and B-2 (trace B, 0.96 to 1.46 seconds). Trace C is treated similarly. Table I is a summary of the primary statistical data. The quantity m_r is the rth moment of the amplitude and is computed from

$$m_r = (1/125) \sum_{i=1}^{125} I_i^r. \tag{1}$$

The quantity λ_r is the rth semi-invariant. The λ_r can be found from the m_r by the set of equations (Cramér, 1946, p. 186, Eqs (15.10.4)).

TABLE I

SUMMARY OF THE STATISTICAL PARMETERS OF SEISMOGRAM TRACES FOR CASES B AND C

Statistical quantity	Case B-1	Case B-2	Case C-1	Case C-2
$I = m_1$	+18.33	+14.05	− 4.424	+ 9.320
$I^2 = m_2$	+53.63×10³	+14.40×10³	+32.84×10³	+12.38×10³
$I^3 = m_3$	+10.62×10⁶	+ 0.7405×10⁶	− 0.6955×10⁶	+ 0.9651×10⁶
$I^4 = m_4$	+17.40×10⁹	+ 0.7741×10⁹	+ 3.679×10⁹	+ 0.5445×10⁹
λ_1	+18.33	+14.05	− 4.425	+ 9.320
λ_2	+53.29×10³	+14.20×10³	+32.82×10³	+12.30×10³
λ_3	+ 7.685×10⁶	+ 0.1481×10⁶	− 0.2599×10⁶	+ 0.6205×10⁶
λ_4	+ 8.207×10⁹	+ 0.1439×10⁹	+ 0.4409×10⁹	+ 0.05328×10⁹
σ	+230.8	+119.2	+181.2	+110.9

$$\begin{aligned} \lambda_1 &= m_1 \\ \lambda_2 &= m_2 - \lambda_1^2 \\ \lambda_3 &= m_3 - 3\lambda_1\lambda_2 - \lambda_1^3 \\ \lambda_4 &= m_4 - 3\lambda_2^2 - 4\lambda_1\lambda_3 - 6\lambda_1^2\lambda_2 - \lambda_1^4. \end{aligned} \tag{2}$$

The semi-invariant λ_2 is of particular importance since the standard deviation σ is given by

$$\sigma = + \sqrt{\lambda_2} \tag{3}$$

Rice (1944) analyzes the frequency distribution $f(I)$ of the amplitude I of a noise current. He derives an exact expression for $f(I)$ which can be expanded in an infinite series, the successive terms of which are of the order of powers of $N^{-1/2}$. The symbol N denotes the number of events per second which give rise to the noise current. This same series is discussed in more detail by Cramér (1946, pp. 222–232). The first three terms of the series for $f(I)$ are

$$\begin{aligned} f(I) = {} & (1/\sigma)\phi^{(0)}(x) - (\lambda_3/6\sigma^4)\phi^{(3)}(x) \\ & + [(\lambda_4/24\sigma^5)\phi^{(4)}(x) + (\lambda_3^2/72\sigma^4)\phi^{(6)}(x)] \cdots \end{aligned} \tag{4}$$

where

$$x = (I - \bar{I})/\sigma. \tag{5}$$

The two terms in the square bracket are treated as one since each term is of the order of $N^{-3/2}$. The function $\phi^{(n)}(x)$, which is the nth derivative of the Gaussian error function, is defined in Eq. (9) of Part I.

One may present statistical data by plotting the frequency function $f(I)$ versus I or by plotting the distribution function $F(I)$ defined by

$$F(I) = \int_{-\infty}^{I} f(x)dx. \tag{6}$$

The frequency function $f(I)$ is defined so that $f(I)dI$ is the probability of finding a value of the noise current in an interval dI centered about the value I. On the other hand $F(I)$ is the probability of finding a value of the noise current in the interval between $-\infty$ and I. The concept of the distribution function is more general than that of the frequency function and consequently it will be used in the present analysis. If (5) is substituted into (6) and the integration carried out, using Eq. (9) of Part I, one has

$$\begin{aligned} F(I) = {} & \phi^{(-1)}(x) - (\lambda_3/6\sigma^3)\phi^{(2)}(x) \\ & + [(\lambda_4/24\sigma^4)\phi^{(3)}(x) + (\lambda_3^2/72\sigma^6)\phi^{(5)}(x)] \cdots \end{aligned} \tag{7}$$

where x is defined in (5).

THE DISTRIBUTION FUNCTION $I(F)$ FOR THE AMPLITUDES

The left member of Eq. (7) can be plotted from the experimental data. Since only 125 values of I are available in each sample, the amplitudes have been grouped into intervals of 50 in order to obtain a smooth behavior. These data

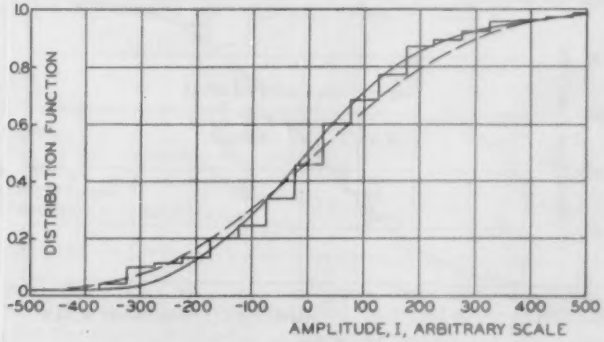

FIG. 1. The cumulative frequency polygon for the amplitudes of the seismic trace from 0.46 to 0.96 seconds for a geophone depth of 75 feet. The solid curve is a plot of the right member of Eq. (7), and the dashed curve is the dominant term only.

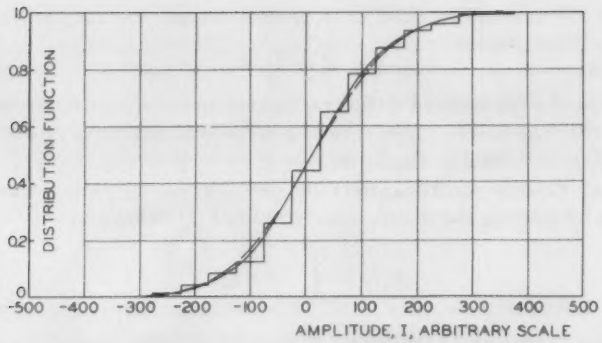

FIG. 2. The cumulative frequency polygon for the amplitudes of the seismic trace from 0.96 to 1.46 seconds for a geophone depth of 75 feet. The solid curve is a plot of the right member of Eq. (7), and the dashed curve is the dominant term only.

are plotted in the usual form of a cumulative frequency polygon in Figures 1 to 4.

The theoretical expression in the right member of (7) can be computed with the aid of the data given in Table I. Figures 1, 2, and 4 each contain two curves. The solid curve is a plot of the right member of Eq. (7) while the dashed curve is a plot of the dominant term $\phi^{(-1)}(x)$ only. These two curves differ so little in Case C-1 that they are drawn as one curve in Figure 3. In each of the figures the agreement between the observed distribution of I and the distribution predicted on the basis of the theoretical premise is close enough to suggest that the theoretical premise constitutes an adequate basis for the study of seismic noise. This is of particular importance since modern work on network theory is often based on the assumption that the statistical properties of the noise background are known.

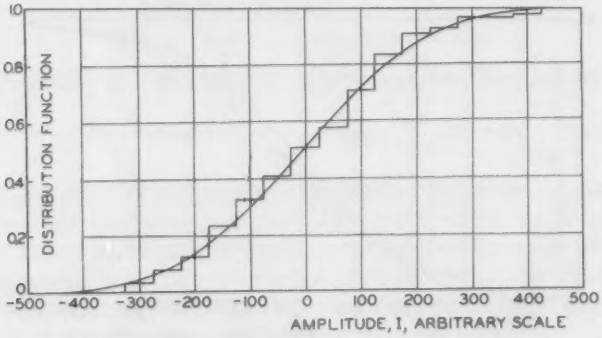

FIG. 3. The cumulative frequency polygon for the amplitudes of the seismic trace from 0.46 to 0.96 seconds for a geophone depth of 125 feet. The solid curve is a plot of the right member of Eq. (7), and the same curve fits the dominant term only.

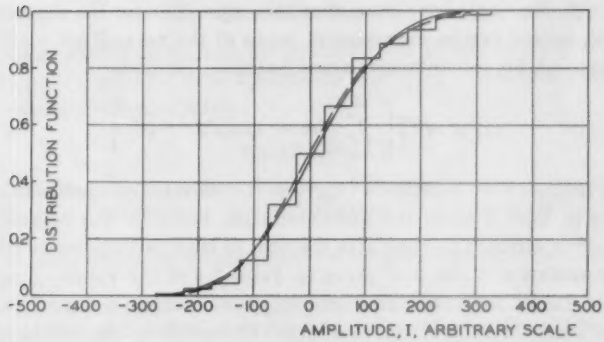

FIG. 4. The cumulative frequency polygon for the amplitudes of the seismic trace from 0.96 to 1.46 seconds for a geophone depth of 125 feet. The solid curve is a plot of the right member of Eq. (7), and the dashed curve is the dominant term only.

It was remarked earlier that the three terms in the right member of Eq. (7) are of the order of $N^{-1/2}$, N^{-1}, $N^{3/2}$, respectively. This means that if the solid and dashed curves differ appreciably, as in Figure 1, the number of events per second which constitute the noise is moderate. On the other hand if the solid and dashed curves agree closely, the number of events per second, N, is such that $\sqrt{N} \gg 1$. It does not appear possible to make more exact statements on the basis of the data at hand.

THE EXPECTED NUMBER OF ZEROS PER SECOND

A second statistical property of a time series that may be studied easily is the number of zeros per second. The number of zeros per second were counted for the four samples of data and the results are given in Table II.

TABLE II

DATA ON ZEROS PER SECOND

Quantity	Case B-1	Case B-2	Case C-1	Case C-2
Total number of zeros	40	29	35	33
Number of zeros per second	80	58	70	66
Expected number of zeros per second by Eq. (9)	90	90	60	60

The problem is analyzed by Rice (1945, Eq. (3.3-11)) who develops the following formula for the expected number of zeros per second.

$$2\left[\int_0^\infty f^2\omega(f)df \Big/ \int_0^\infty \omega(f)df\right]^{1/2}. \tag{8}$$

Horton (1956, Eq. (23)) has shown that this expression for the expected number of zeros per second can be expressed in terms of the normalized coefficients c_{2m}^* of the expansion for the autocorrelation function. He finds

$$(1/\sqrt{2}\pi T)\left[\sum_{m=0}^{\infty}(2m+1)c_{2m}^*\phi^{(2m)}(0)\right]^{1/2} \tag{9}$$

where the sequence of coefficients $\{c_{2m}^*\}$ is the normalized coefficients that were introduced in Part I when the autocorrelation function was represented by a Gram-Charlier series. The time T is the unit of time introduced in the analysis. When the numerical value of T given in Table I and the values of c_{2m}^* given in Table II of Part I are substituted into (9), one obtains a value of the expected number of zeros for each of the two cases. These values are tabulated in Table II.

When the autocorrelation functions $\psi(\tau)$ were computed for each of the traces (see Eq. (19), Part I), all 250 values were used. This means that only one autocorrelation function, only one sequence of coefficients $\{c_{2m}^*\}$, and only one value of the expected number of zeros per second are available for each trace.

It is evident that the number of axis crossings in one half second is small so that large fluctuations will occur. This means that one can only say that in the data presented in Table II the difference between the observations and the predictions is as good as one can expect.

Although the material presented in Parts I and II represent a large amount of numerical analysis, the results represent a very small amount of seismic data so that only tentative conclusions can be drawn. The most important conclusions are:

1. The theory of shot noise as presented by Rice (1944, 1945) offers a good first approximation to the statistical properties of the noise background of a seismogram trace.

2. There is fairly clear evidence that the noise structure of the seismogram becomes appreciably more complicated as the point of observation approaches the surface. The two parts C-1 and C-2 of the trace for the geophone at 125 feet depth are more homogeneous than the two parts B-1 and B-2 of the trace for the geophone at 75 feet. The autocorrelation function resulting from a geophone at 10 feet depth is more complicated than the functions obtained from the deeper geophones.

3. The preliminary results obtained in this analysis are promising and it appears likely that a systematic analysis of a large number of traces would yield much useful information about the dependence of the statistical parameters on geophone depth, record time, etc. Now that a large amount of seismic data is available on magnetic discs and tape, the reading and computing of the data could be done automatically.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 268–274, 3 FIGS.

ATTENUATION OF SOUND IN ROCKS*

M. KRISHNAMURTHI† AND S. BALAKRISHNA†

ABSTRACT

An experimental method used for measurement of absorption of sound is described briefly in this paper and attenuation in the case of a few rocks has been determined at 3 frequencies in the range of 2 to 6 Mc/s. The results show that the absorption increases rapidly with increasing frequency in the case of most rocks investigated.

INTRODUCTION

Dissipation of acoustic energy in solid media may be due to several factors, important among them being internal friction, thermal conductivity, scattering and diffusion. The relative importance of these factors depends upon the frequency of the acoustic waves and the granular structure of the solid (i.e. size of the grain, closeness of their packing etc.). Mason and McSkimin (1947) carried out measurement of attenuation of sound in several metals and glasses and studied the effect of grain size and frequency on the amount of sound energy dissipated in the medium. They find that, for metals, the attenuation of both longitudinal and torsional waves is proportional to frequency at the lower frequencies and to the fourth power of frequency at the higher frequencies. At much higher frequencies where the grain size is more than three times the wavelength, some amount of attenuation occurs due to a process of diffusion which is independent of frequency. The present work on some Indian rocks was therefore undertaken in an effort to correlate the structure of these rocks with their ultrasonic propagation characteristics. In an earlier paper, one of the authors (1955) has shown that these rocks which are in the nature of polycrystalline aggregates can be considered to be isotropic so far as their elastic properties are concerned. In measuring the ultrasonic attenuation also the isotropic nature of these rocks has been assumed.

EXPERIMENTAL TECHNIQUE

An arrangement similar to the one described by the authors (1953) is used for generating and receiving a pulsed ultrasonic beam in a cell containing water. The specimen under investigation is interposed normal to the beam. A block diagram of the apparatus is given in Figure 1.

As in all other methods of measuring the absorption, the present method also involves measurement of intensity when a variable distance in the medium is traversed by the sound beam. The absorption coefficient, α, is then obtained from the relation $I_x = I_0 \exp(-2\alpha X)$. Therefore

$$\log I_x = -2\alpha X + \log I_0.$$

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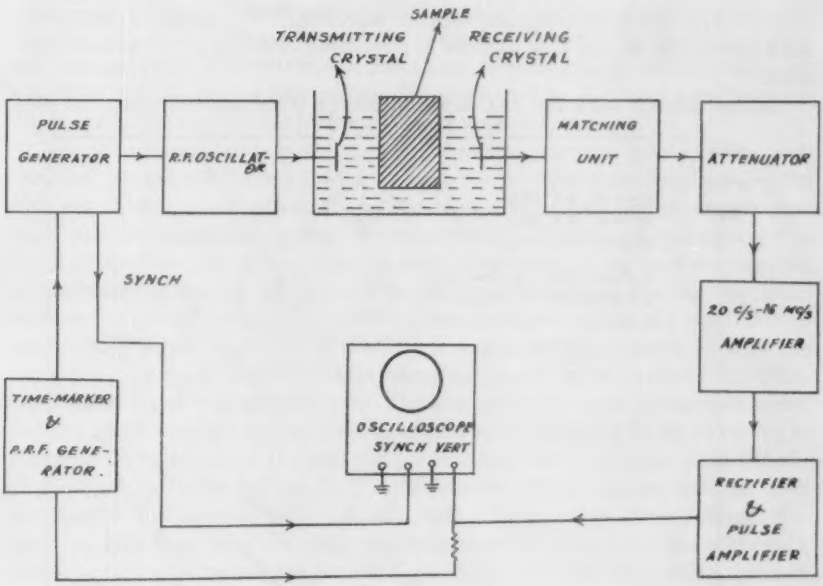

FIG. 1. Schematic diagram.

In this experiment, however, no attempt has been made to determine the attenuation of the longitudinal and torsional modes separately, but only the total loss in acoustic energy per unit distance traversed has been determined. As the sound beam is incident normally on the surface of the rock, there is no refraction of either component within the rock. Hence on emergence, the two components will reinforce each other if the thickness is chosen to contain an integral multiple of the wave lengths of both the components. The proper choice of each thickness ensures that there is no loss of energy due to destructive interference between the two components. The pulse width is chosen such that interference due to multiple reflection also is avoided. The other two dimensions of the sample, namely the length and the breadth, are not very critical except that

TABLE I

ATTENUATION OF SOUND IN DECCANTRAP

Thickness	2.1 Mc/s	3.5 Mc/s	6.3 Mc/s
17.3	12.0	14.4	25.0
15.0	11.2	12.5	21.3
12.8	10.7	10.5	17.2
10.4	10.2	8.1	14.0
7.7	9.5	—	8.0

they must be very large compared with the wavelength. All the plates used in this work are squares of 3 cm side, and can be considered as media with infinite boundaries.

In the present work the loss of sound energy is determined when the rock

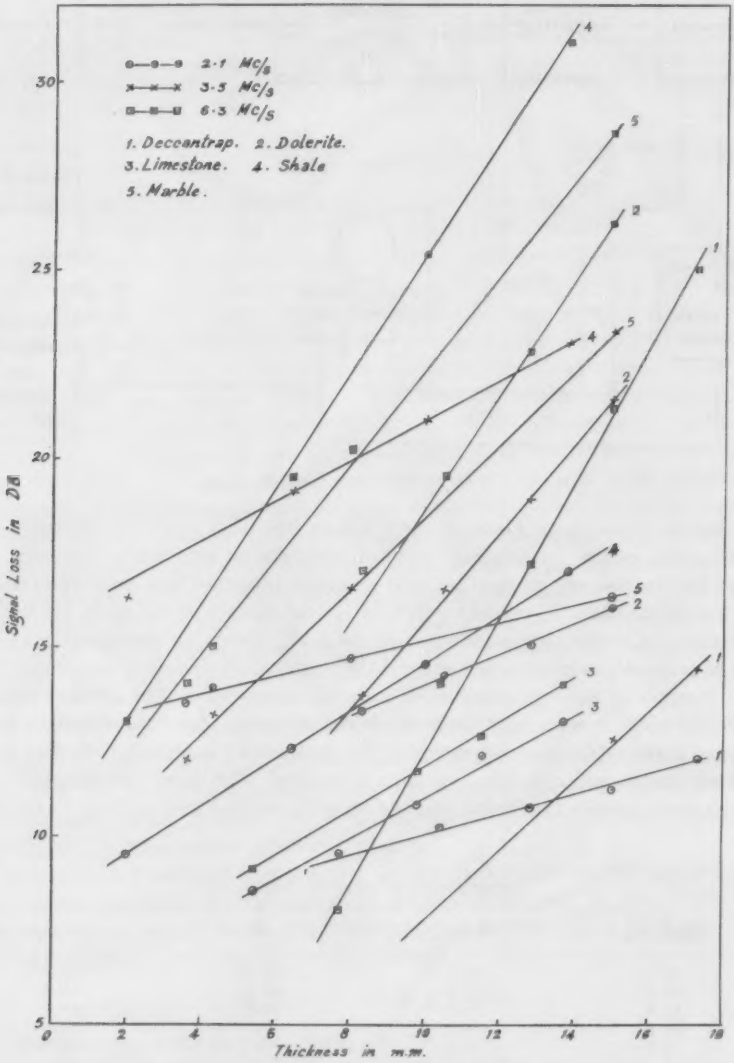

FIG. 2. Signal loss in db vs. thickness in millimeters.

samples of different thicknesses are interposed in the path of ultrasonic beam. For this purpose a calibrated attenuator is inserted between the receiving crystal and the amplifier. This attenuator has three decades with an additional 30 db switch so that maximum attenuation of 130 db can be measured correct to 0.1 db. It reads correctly in the frequency range 0–30 Mc/s.

To take measurements of absorption, the receiving crystal is set at some position and the attenuator is adjusted so that the received pulse height coincides with one of the graduations on the oscilloscope screen which carries a centimeter scale, and corresponding reading of the attenuator is noted. The attenuator is again adjusted so that it may give the same pulse height after each rock sample is interposed, at normal incidence. The difference of the two readings gives the attenuation caused in the particular rock sample together with the losses due to reflection. The loss in the liquid medium is neglected when compared with the loss in the rock and it is assumed that reflection loss will be the same for the different thicknesses of rock samples used. The absorption for each thickness is noted and the graph is drawn between the thickness and absorption in db as shown in Figure 2. The gradient of the straight line obtained in this manner gives the absorption per centimeter of the rock. Four different thicknesses are used for each rock sample and the absorption of each rock is measured at three different frequencies. The accuracy is limited by the determination of the thickness of the rock sample used and adjusting the pulse height before and after interposing the rock in the ultrasonic beam.

RESULTS AND DISCUSSION

The results obtained in the present investigation are given in the following tables. The thickness is given in millimeters. The attenuation is measured in db per centimeter. Attenuation measurements are made at three different frequencies.

TABLE II

ATTENUATION OF SOUND IN DOLERITE

Thickness	2.1 Mc/s	3.5 Mc/s	6.3 Mc/s
15.0	16.0	21.5	26.2
12.2	15.0	18.9	22.8
10.5	14.2	16.5	19.5
8.3	13.3	13.7	17.0

TABLE III

ATTENUATION OF SOUND IN LIMESTONE

Thickness	2.1 Mc/s	6.3 Mc/s
13.7	13.0	14.0
11.5	12.1	12.6
9.8	10.8	11.7
5.4	8.5	9.1

The results obtained in the present investigation are given in the following tables. The thickness is given in millimeters. The attenuation is measured in db per centimeter. Attenuation measurements are made at three different frequencies. Tables I to V give the signal loss in db when different thicknesses of a given rock are inserted in the sound beam.

TABLE IV

ATTENUATION OF SOUND IN SHALE

Thickness	2.1 Mc/s	3.5 Mc/s	6.3 Mc/s
13.8	17.0	23.0	31.0
10.0	14.5	21.0	25.3
6.4	12.3	19.1	19.5
2.0	9.5	16.3	13.0

TABLE V

ATTENUATION OF SOUND IN MARBLE

Thickness	2.1 Mc/s	3.54 Mc/s	6.3 Mc/s
15.0	16.3	23.3	28.6
8.0	14.7	16.5	20.2
4.3	13.9	13.2	15.0
3.6	13.5	12.0	14.0

The attenuation in rocks, as calculated from the gradients of the graphs in Figure 2 at three different frequencies are tabulated in Table VI. The grain sizes in these samples have been determined using a panphot polarising microscope and they are also given in the table.

The attenuation is plotted as a function of frequency as shown in Figure 3. The numbers given in the graph correspond to the serial numbers given in Table VI.

The above results show that attenuation in rocks is generally higher than in amorphous substances where the grain size is negligible or in metals of even large grain size or even in gels. This is to be ascribed to the heterogeneous nature of the rock, comparatively loose packing, and also to the binding material present

TABLE VI

VARIATION OF ATTENUATION OF SOUND IN ROCKS WITH FREQUENCY

Serial No.	Rock	Grain size in mm	2.1 Mc/s	3.54 Mc/s	6.3 Mc/s
1	Deccantrap	0.30	2.6	9.0	17.6
2	Dolerite	0.28	5.0	12.0	15.2
3	Limestone	0.05	5.5	5.6	5.7
4	Shale	0.15	6.0	5.8	15.5
5	Marble	0.20	2.4	9.8	12.5

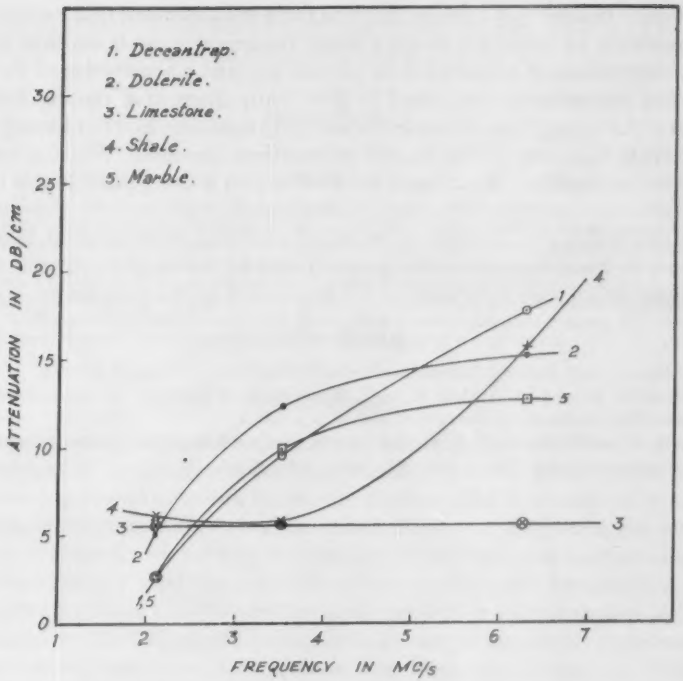

FIG. 3. Variation of attenuation in rocks with frequency.

in the rock. The comparatively higher attenuation coefficients are therefore to be expected in rocks.

As in many other solid substances, the attenuation in rocks increases with increasing frequency as can be seen from the Figure 3. As the range of frequencies, in which the present measurements were carried out, is not large enough no definite conclusion can be drawn regarding the relationship between attenuation and frequency.

It is interesting to note that in limestone which is fine grained, homogeneous, and closely compacted the variation of attenuation is slight but linear with frequency. This is probably due to the absence of scattering. In shale which has a similar grain size, but doubtful mineralogical composition and loose packing there is a rapid increase in attenuation with frequency. This is probably because of large scattering. In the other three rocks viz. deccantrap, dolerite and marble the grain size is much larger and comparable with the wavelengths used. Under such conditions, the attenuation tends to become independent of frequency as is seen from the flattening of the $(\alpha - f)$ curves in Figure 3.

No definite conclusions can be drawn in rocks with reference to the dependence of attenuation on frequency unless a larger frequency range is covered. Studies on the dependence of attenuation on particle size and a verification of Rayleigh scattering phenomenon are bound to give many interesting results. For such studies rocks belonging to the same division (e.g. metamorphic) but having different particle size must be taken and attenuations measured. Marbles are best suited for such studies. An attempt in this direction is being made in this laboratory.

In conclusion the authors desire to acknowledge their grateful thanks to Professor S. Bhagavantam for his guidance and helpful suggestions, throughout this work, which were invaluable in the realization of this programme.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 275–285, 10 FIGS.

A SEISMIC MODEL STUDY OF THE PHASE VELOCITY METHOD OF EXPLORATION*

FRANK PRESS†

ABSTRACT

Variations in the phase velocity of earthquake-generated surface waves have been used to determine local variations in the thickness of the earth's crust. It is of interest to determine whether this method can be used to delineate structures encountered by the exploration geophysicist. A seismic model study of the effect of thickness changes, lithology changes, faults and scarps, on the phase velocity of surface waves was carried out. It is demonstrated that all of these structures produce measurable variations in the phase velocity of surface waves. Additional information is required, however, to give a unique interpretation of a given phase velocity variation in terms of a particular structure. Some remarks on the phenomenon of returning ground roll are made.

INTRODUCTION

Some of the basic techniques used in exploration seismology stem from methods developed in earthquake seismology. Recently a new method (Press, 1956) for delineating crustal structure by the use of phase velocity variations of earthquake generated surface waves was described. Unlike current practice in seismic exploration where travel times of impulses are determined, this method involves the measurement of local phase velocity of waves of a given frequency. A preliminary evaluation of the applicability of this method in seismic exploration was made using an ultrasonic model analog. In this paper we report on model studies of phase velocity variations due to faults, scarps, thickness changes, and lithology changes.

THE METHOD

When a disturbance occurs in an elastic half-space in which the elastic constants vary with depth, part of the energy is radiated as body waves and part propagates horizontally, guided by one or more channels associated with particular variations of the elastic parameters. The free surface usually forms an upper boundary to the channel in which case the guided waves are the familiar surface waves. Rayleigh waves, Love waves, Stoneley waves, ground roll, microseisms are examples of guided waves.

Guided waves are dispersed and as a consequence two velocities must be considered, the phase velocity c and the group velocity U. The phase velocity is the local velocity of propagation of a point of constant phase such as a trough or peak. It depends on period through an equation which contains as parameters the dimensions of the channel and the elastic constants within and adjacent to the channel. Phase velocity is sensitive to lateral variations in elastic parameters.

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For example, when a dispersed train of surface waves crosses a boundary, such as a fault, between two media having different vertical velocity distributions, the waves assume the phase velocity appropriate to the new medium; refraction occurs at the boundary, the paths of the rays being determined by the phase velocities according to the usual law of refraction. The overall travel time of a group of waves of a given frequency is determined by the group velocities (Bullen, 1953, p. 106–107).

Data from a single seismogram are sufficient to construct a curve of group velocity versus frequency. By comparison with theoretical group velocity curves constructed under different assumptions one can infer the average properties of the medium between the source and the seismograph (see for example, Ewing and Press, 1956).

To obtain indications of local variations in the vertical distribution of elastic parameters, one must use phase velocity. Phase velocity can be determined together with direction of approach from the differential arrival times of individual crests and troughs recorded at three seismographs arranged in a triangular array.

The linear dimensions of the array must be of the order of a wavelength. Smaller separations do not permit precise determinations of differential times whereas longer separations lead to problems of correlating events at each of the stations. Criteria for determining separation distances have been discussed by Evernden (1953).

The phase velocity method is based on the interpretation of local variations in phase velocity using changes in the vertical distribution of elastic parameters. Actually a unique interpretation is not possible since both thickness changes and velocity changes can produce similar phase velocity changes. However, the use of additional information, such as that derived from geological plausibility can sometimes lead to unique interpretations. Although interpretations can be made by comparing observed and theoretical phase velocity curves, a more direct method, one involving fewer assumptions, is to compare observed phase velocity with experimentally determined standard curves (Press, 1956).

PROCEDURE

The two-dimensional seismic model techniques described by Oliver, Press and Ewing (1954), were used. Since dispersion of surface waves is the same for two-dimensional propagation from a line source and three-dimensional propagation from a point source there is no loss in generality of the results. The fabrication of the models is simple and complexities introduced by refraction of surface waves are eliminated. Further simplification is introduced by the use of flexural waves. These waves are easy to excite and the equation governing their dispersion is amenable to fast computation. Although flexural waves do not exist in the earth, they share with naturally occurring waves the general characteristics of guided waves. Satô (1951) demonstrated the connection between flexural waves and the M_2 branch of Rayleigh waves.

Flexural waves were excited in two-dimensional models of structures analogous to those encountered in the field. The waves were observed along spreads crossing the structure, detector spacing being sufficiently small to permit measurement of the resulting phase velocity variation. Models were fabricated from 1/16 inch sheets of plexiglass and brass.

RESULTS

Thickness Change

This model consists of a plexiglass strip 90 inches long in which the thickness changes from $\frac{1}{4}$ inch to $\frac{1}{8}$ inch in a distance of 1 inch at the midpoint. A spread was placed in the range $41\frac{1}{2}$–$47\frac{1}{2}$ inches so as to cross the thickness change with detector spacing of $\frac{1}{4}$ inch (Figure 1).

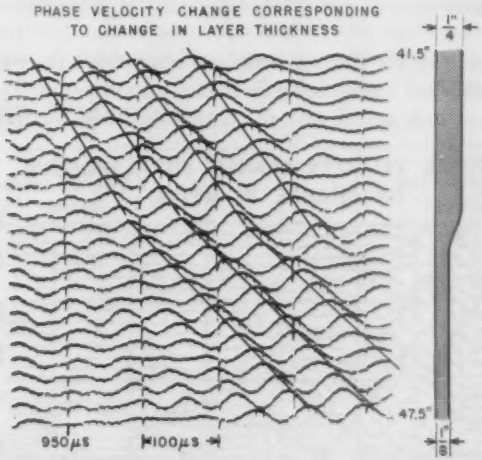

FIG. 1. Model seismogram indicating phase velocity change corresponding to thickness change.

Individual crests and troughs may be followed across the structural change, demonstrating the coherence of the waves. Clearly evident is the decrease in phase velocity of the individual waves as they cross from the thick layer to the thin layer. One method of analyzing these data is to use phase velocity for one zone as a standard against which phase velocity data for other zones may be compared. If the propagating medium is one in which structural changes consist only of thickness changes (each layer of the section changing in the same proportion), then the period change for a given phase velocity is proportional to the thickness change. For Figure 2, the experimentally determined phase velocities are plotted as a function of period. The data for the $\frac{1}{4}$ inch zone were extended by computing two points using the flexural wave period equation (Oliver, Press and Ewing, 1954, p. 210). Taking the curve for $H = \frac{1}{4}$ inch as a standard, each phase

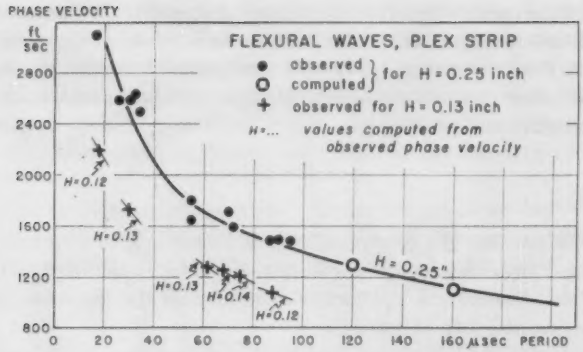

FIG. 2. Graphical interpretation of phase velocity change in terms of thickness change.

velocity observation in the thinner zone was interpreted in terms of a reduced thickness, the computed values being indicated on the figure. The average computed value of 0.13 inch agrees with the actual thickness for this zone.

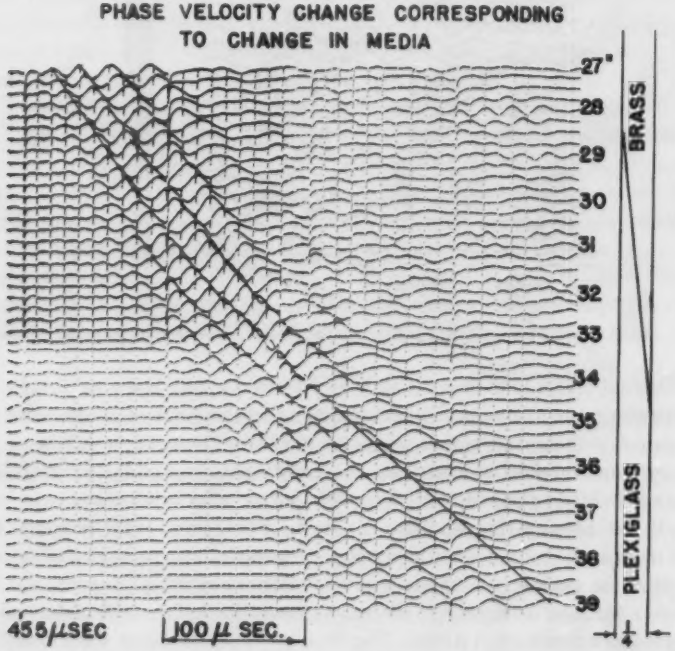

FIG. 3. Model seismogram indicating phase velocity change corresponding to lithology change.

This analog, simple as it is, demonstrates on the ultrasonic scale the method used by Press (1956) for determining thickness changes of the earth's crust in California.

Lithology Change

This structure was modeled by a gradual wedgeout from a $\frac{1}{4}$ inch layer of brass to a $\frac{1}{4}$ inch layer of plexiglass over a distance of 6 inches. The impulsive source was located in the brass layer, 32 inches from the midpoint of the wedgeout and observations were made in the range 27–39 inches (Figure 3). Individual crests and troughs may be followed across the simulated lithology change, the gradual decrease in phase velocity with increasing penetration into the plexiglass zone being evident on the seismogram.

Phase velocities were measured for different periods at several positions along the spread. The results are presented in Figure 4 where the location of the measurement is specified in terms of percent brass in the section. In the same figure curves are presented which were computed from the frequency equation of flex-

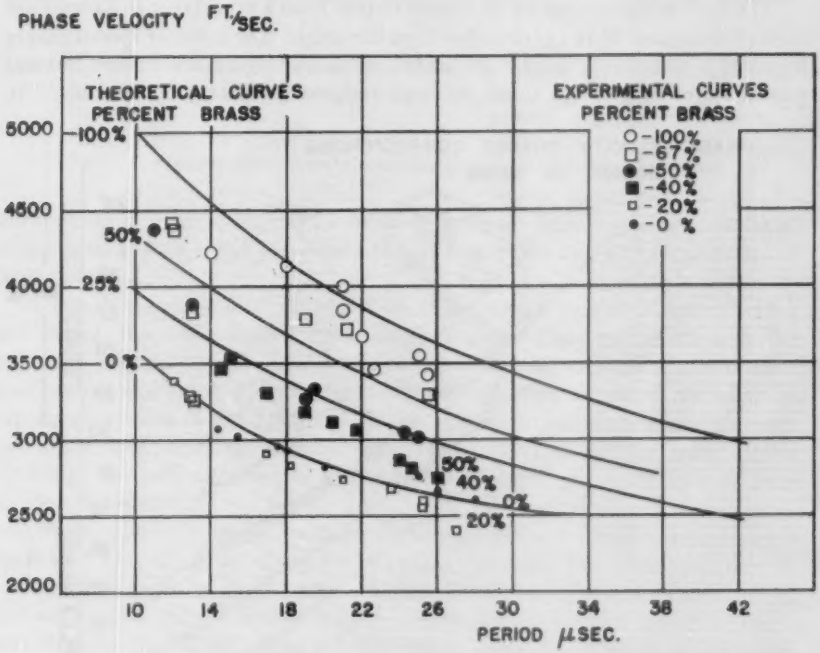

FIG. 4. Comparison of experimental and theoretical phase velocities in a region of lithology change. Theoretical curves based on homogeneous layer with weighted values for elastic constants according to proportion of brass to plexiglass.

ural waves (Oliver, Press and Ewing, 1954) with weighted values for the elastic constants inserted according to the proportion of brass to plexiglass in the section. The experimental points for 0 percent and 100 percent brass fit the corresponding computed curves reasonably well. The phase velocity data for the composite sections fall between the pure brass and pure plexiglass curves, but show no systematic agreement with the corresponding computed curves. The lack of systematic agreement between experimental and computed values in the composite zone cannot be interpreted until the theory for flexural waves in a two-layered plate becomes available. Then the validity of phase velocity computations using weighted values for elastic constants can be examined.

This experiment demonstrates how phase velocity variations may be produced by lithology changes. It is not established that composition of a section can be determined in a composite zone, although the occurrence of such a zone may be detectable.

Fault

The fault is represented by an abrupt change from a brass layer to a plexiglass layer at a distance of 29 15/16 inches from the source. The detector spread ranges from $23\frac{3}{4}$ to 36 inches (Figure 5). Indicated on the seismogram are incident flexural waves, waves transmitted across the fault and waves reflected by the fault. The

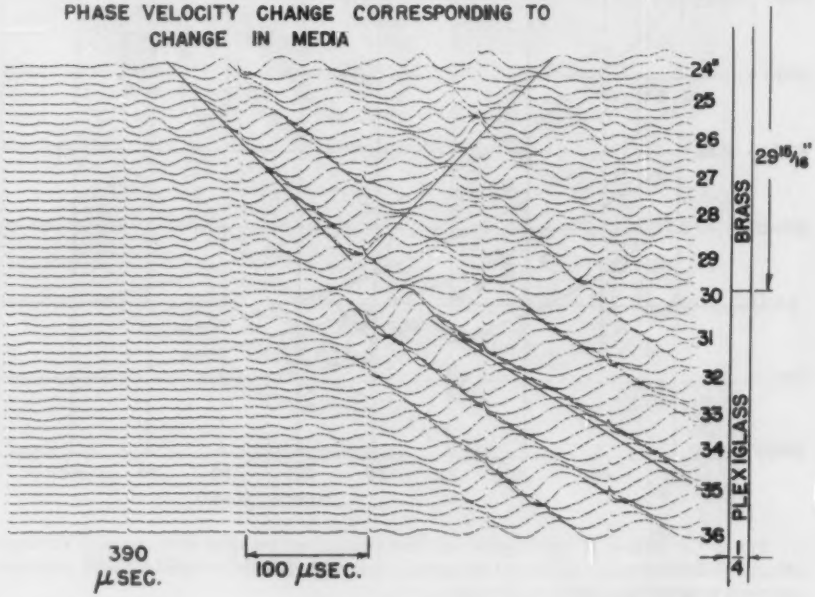

FIG. 5. Model seismogram indicating phase velocity change corresponding to fault.

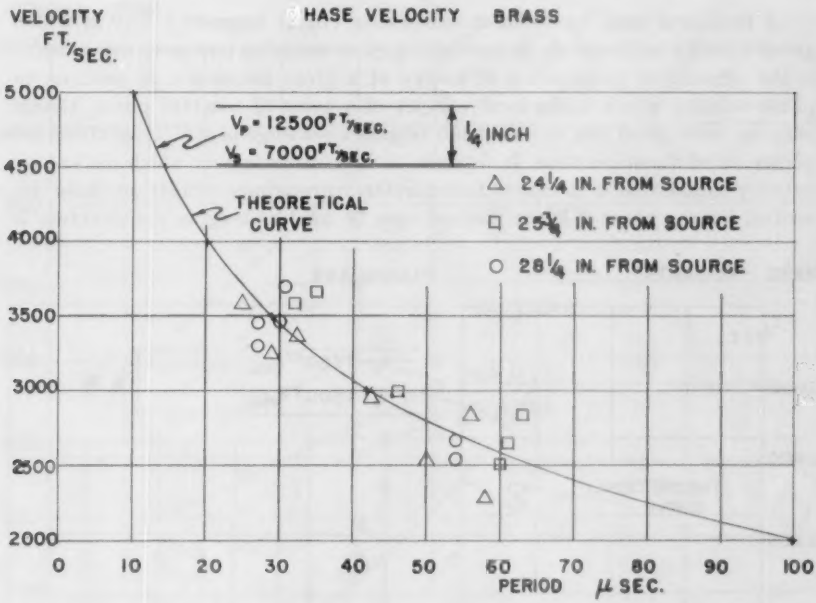

FIG. 6. Comparison of experimental and theoretical phase velocities in brass zone.

abrupt change in phase velocity as the waves cross the fault is apparent. An interesting phenomenon is the occurrence of standing waves and a phase shift in the fault vicinity.

These data will be interpreted by use of theoretical curves. Phase velocities and periods were read directly from the seismograms at several locations in the brass and plexiglass zones. Theoretical curves computed with use of appropriate longitudinal and shear velocities for plexiglass and brass are presented with the experimental data in Figures 6 and 7. The agreement is considered satisfactory and could have been improved by more sophisticated methods of reducing the data, e.g., by the use of machine methods for computing phase shifts for the harmonic components.

Group velocity analysis has been discussed by many investigators (see for example Ewing, Jardetzky, and Press, 1957, chapter 4). The usual procedure is to determine an experimental group velocity curve from the overall travel time and distance for each of several periods. The experimental curve is used to select one of many theoretical group velocity curves based on different assumptions of structure. When the path crosses more than one structure, allowance must be made for the group velocity in each structure. This method of analysis is not suitable for local exploration since group velocity determined this way is affected by variations over the entire propagation path.

A technique used by Brilliant and Ewing (1954) suggests a way in which group velocity methods can be used with greater resolving power. Group velocity is the velocity of propagation of energy of a given frequency, in contrast to phase velocity which is the local velocity of a point of constant phase. Group velocity determined this way does not require knowledge of structures traversed earlier, or of the origin time. It depends on the structure over which the energy velocity measurement is made. Interpretation procedures similar to those described for the phase velocity method may be used as long as the structure is

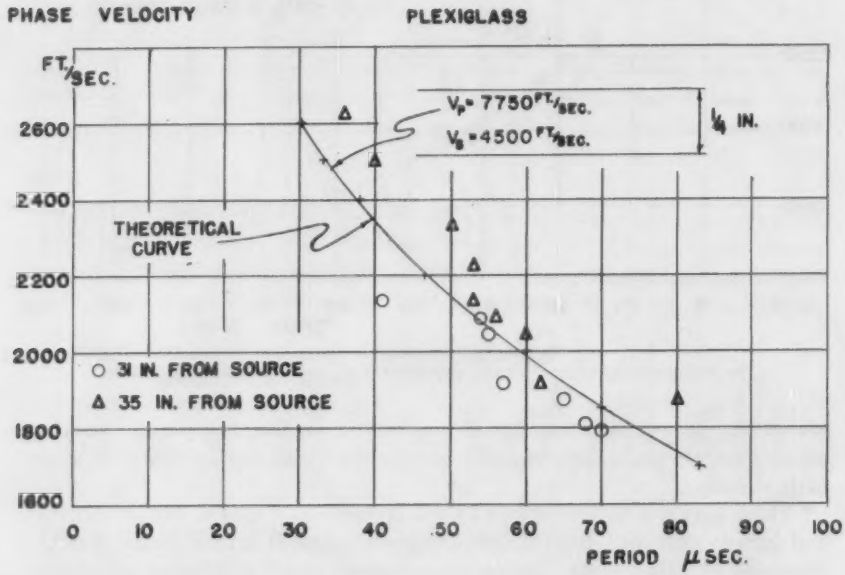

FIG. 7. Comparison of experimental and theoretical phase velocities in plexiglass zone.

homogeneous over the much longer distance required to measure the velocity of a wave group of a given frequency.

As an example, this method will be applied to the fault model. The waves in the plexiglass portion of the seismogram of Figure 5 are assigned numbers. Wave number is plotted as a function of arrival time for several detector positions. By taking slopes of these curves, period as a function of arrival time can be obtained with detector distance as parameter. From these data curves of arrival time versus distance may be constructed for several periods as in Figure 8. The slopes of the arrival time curves yield group velocity for each of the periods. Experimental group velocity determined in this manner is compared with a theoretical group velocity curve appropriate for a ¼ inch plexiglass layer in Figure 9.

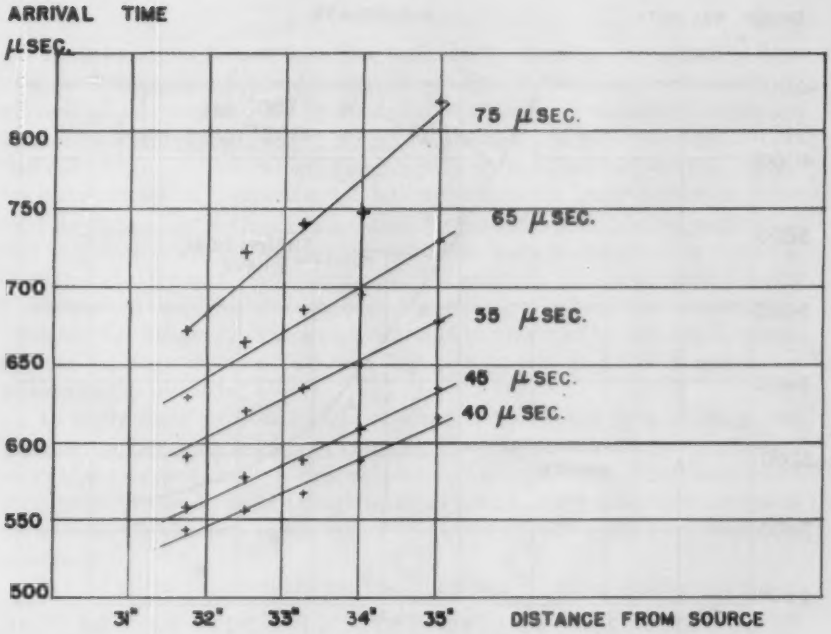

FIG. 8. Travel time curves for several periods in plexiglass zone.

Scarp

Reflected surface waves were indicated in the fault model. The scarp model is presented the better to demonstrate this phenomenon. Reflection of body waves has received much attention. To a lesser degree reflected surface wave pulses have been studied in the ultrasonic scale. The reflection of a train of dispersed surface waves has perhaps received most attention by field seismologists who have observed this phenomenon as returning ground roll. Faults, and topographic changes have been identified as the cause of ground roll reflection.

Reflected flexural waves were excited in a model consisting of an abruptly terminated brass strip (Figure 10). Incident and reflected waves are readily identifiable on the seismogram, and the standing wave pattern formed by their interference is evident. The reflected train is more pronounced in the scarp model than in the fault model as may be seen by comparing Figures 5 and 10, a result which is not unexpected.

The reflected train is longer, a consequence of dispersion and the accompanying stretching of the wave train with increasing propagation distance. The distance between nodes in the standing wave region is about $\frac{7}{8}$ inches, agreeing with the value for half wavelength of 60 μs period flexural waves.

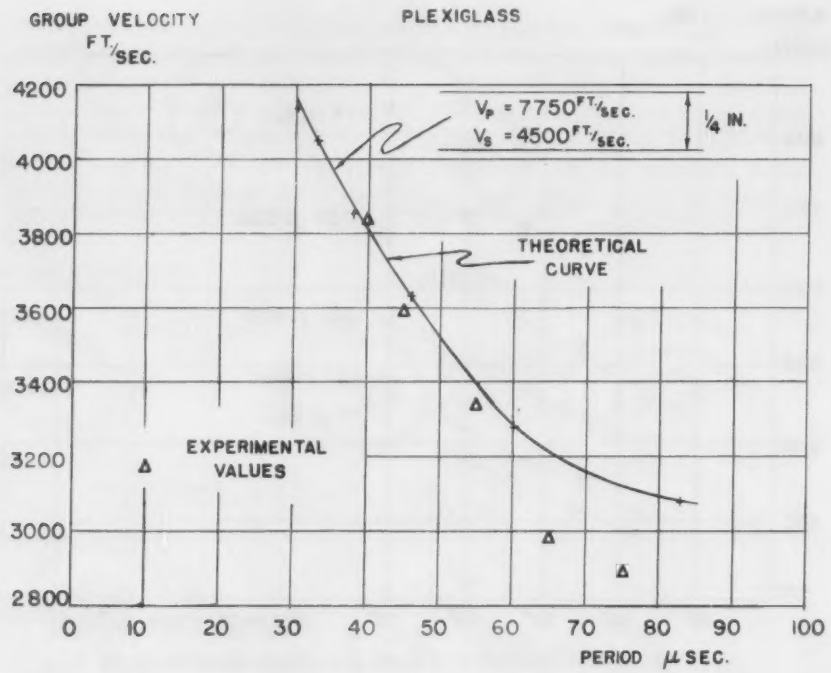

FIG. 9. Comparison of theoretical and experimental group velocity in plexiglass zone.

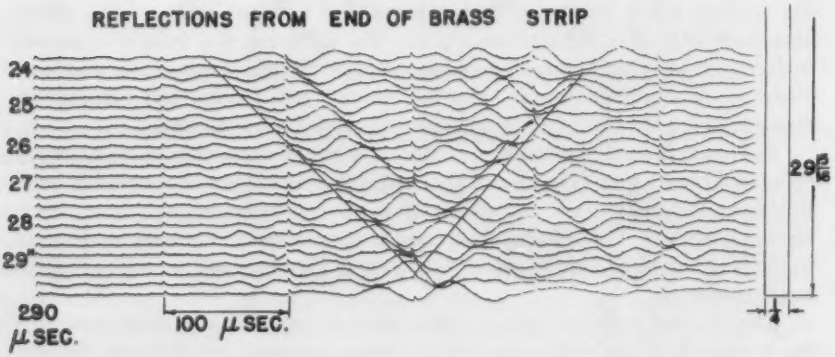

FIG. 10. Model seismogram of flexural waves reflected from end of a strip (scarp).

DISCUSSION

These examples demonstrate how horizontally traveling energy in the form of guided waves can indicate structural changes of the kind encountered by exploration geophysicists. Interpretation of phase velocity changes is not unique in that thickness changes cannot readily be distinguished from lithology changes without additional information. This suggests methods of interpretation involving intercomparison of experimental data rather than the use of theoretical phase velocity curves. Phase velocity anomalies, for example, could play an exploration role similar to gravity anomalies or anomalous leads in fan shooting methods. A further analogy with gravity is the effect of an entire section on phase velocity in contrast to mapping of single beds by refraction and reflection techniques. Thus overall changes in section such as would be produced by salt domes, porosity and lithology changes, basement highs, reefs, etc., might be examined by phase velocity methods.

To apply these methods in field exploration, one would have to use guided waves in the frequency range 1 to 1/10 cps. These low frequencies are required in order to obtain penetration to depths of interest in exploration. There is no doubt that waves in this frequency range occur in nature. Earthquake surface waves are an example of waves at one end of this band whereas ground roll limits the other end.

In view of the success of the method when used in crustal studies and model studies, a field research program seems warranted. This program should concern itself with methods of excitation of guided waves in the frequency band of interest, methods of recording these waves and computing their phase velocity automatically, and methods of interpretation.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 286–308, 12 FIGS.

THE GULF SEISMIC PROFILE PRINTER*

E. M. PALMER†

ABSTRACT

A seismic recording system has been developed in which seismic sections, printed photographically in variable-density form, simulate geologic cross-sections. The seismic signals recorded from geophone stations arranged for continuous reflection center-point control are presented in a sequence of vertical tracks. The tracks are adjusted for known corrections and reproduced at a selected horizontal scale. Prints of the variable-density section exhibit all events and their interrelationships for ready recognition and appraisal.

The printer mechanism reduces seismic information to a uniform time basis, with weathering and elevation corrections to datum, and with stepout corrections in which account is taken of changing wave-front velocity with vertical travel-path time.

The original field records comprise variable-density tracks on strips of 70-mm film. In the printer, individual record tracks are successively scanned and transferred to a continuous sheet of film by contact printing. Punched cards supply correction data to mechanisms which displace each record track according to the desired corrections. Normal and special printing functions are automatically performed.

INTRODUCTION

Successful mapping by the reflection seismograph is founded upon the recognition of reflected events and analysis of the detailed relationships of all pertinent information embodied in the set of seismic data. Examination and comparison of oscillographic recordings trace by trace and record by record for line-up of events is an uncertain and painstaking process. Transposition of the events thus chosen to points on cross-section paper is burdensome. The potential contribution of those events which happen not to be chosen for plotting is inevitably lost, and the events which are plotted lose their identity. Effective employment of outstanding reflected events, and those latent but not readily perceivable, may be facilitated by the manner in which they are presented. An adequate presentation should obviate the laborious steps of recognition, calculation, and plotting, and should make possible rapid evaluation of the quality, correlation, and significance of the entire array of events. An adequate presentation should in fact be a seismic counterpart of a geologic cross-section.

The Gulf Seismic Profile Printer performs the final step in a system of seismic recording leading to the presentation of such a section profile. The presentation of the seismic data from a continuous line of sampling stations is photographically printed, and exhibits the data corrected to a selected datum. Variable-density modulation uniquely depicts reflection features, and the analogy to a geologic section is striking (Figs. 1a, 1b, 1c, 1d, and 1e).

HISTORICAL BACKGROUND

Historically, the use of the variable-density process in seismic recording probably originated with the late Frank Rieber. In a patent applied for in 1934,

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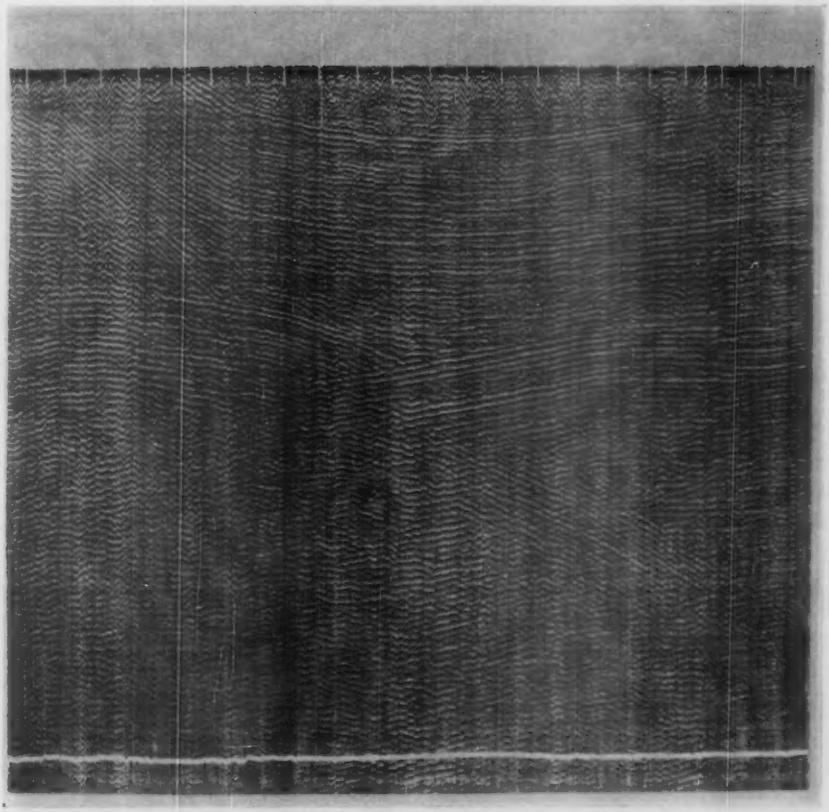

FIG. 1a. Variable-density profile print of seismic traverse, about 3½ miles in horizontal extent, across complex geologic structure. Profile datum is the line across top of section. Band at bottom is about 3.6 seconds below datum.

Rieber (1936a) broadly claims means for recording earth vibrations "in the form of a phonographically reproducible record," and describes the preferred form of record as a variable-density recording on photographic film. He employed such recording for analysis of complex reflection patterns and developed a system of "controlled directional sensitivity" (Rieber, 1936b, 1936c). In pursuing a line of thinking in terms of reproducible records in this period, Rieber was indeed a pioneer.

The type of directional analysis which Rieber ultimately developed and called the "Sonograph" (Rieber, 1937) utilizes a re-recording step in which light passes through slits in proximity to the moving variable-density tracks of an original film record. The light thus modulated by the record tracks illuminates a photocell. The composite signal is amplified and filtered, and a pen draws out a correspond-

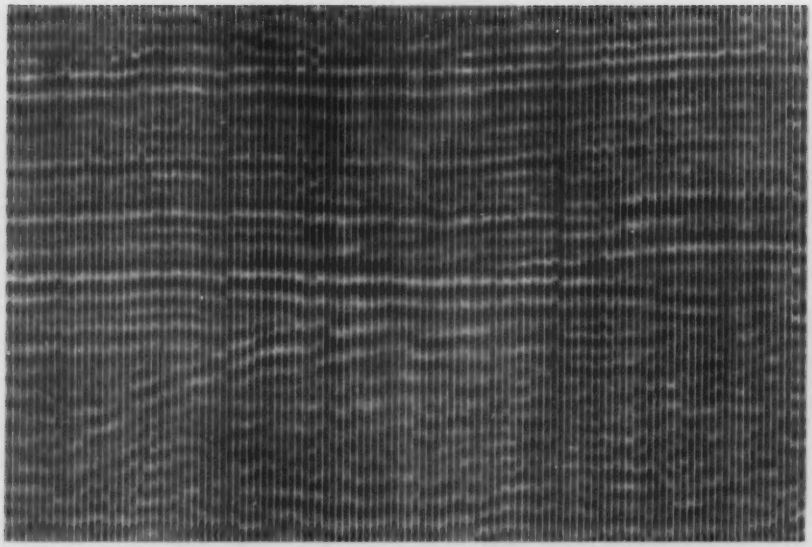

FIG. 1b. Portion of variable-density profile exhibiting fault and diffraction pattern.

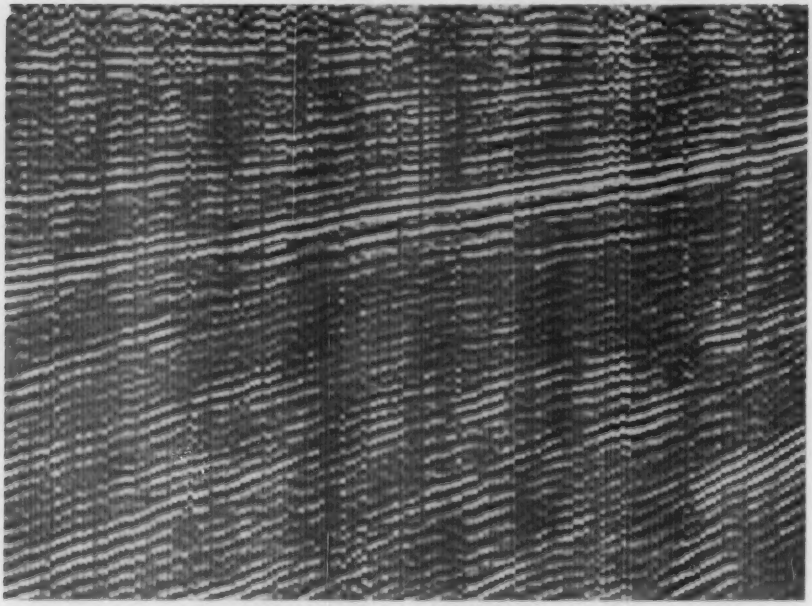

FIG. 1c. Portion of variable-density profile showing convergence.

ing variable-amplitude trace. Systematic variation of phase positions of the slits for successive re-recording cycles, resulting in a set of traces for each record, gives rise to the directional analysis.

In 1938 the Gulf Research & Development Company acquired licenses under Rieber patents and purchased a set of field recording and office re-recording equipment. As a research tool, this apparatus has afforded valuable experience in the basic concept of the Sonograph and in other re-recording techniques for which the equipment could be adapted. The original equipment was soon modified

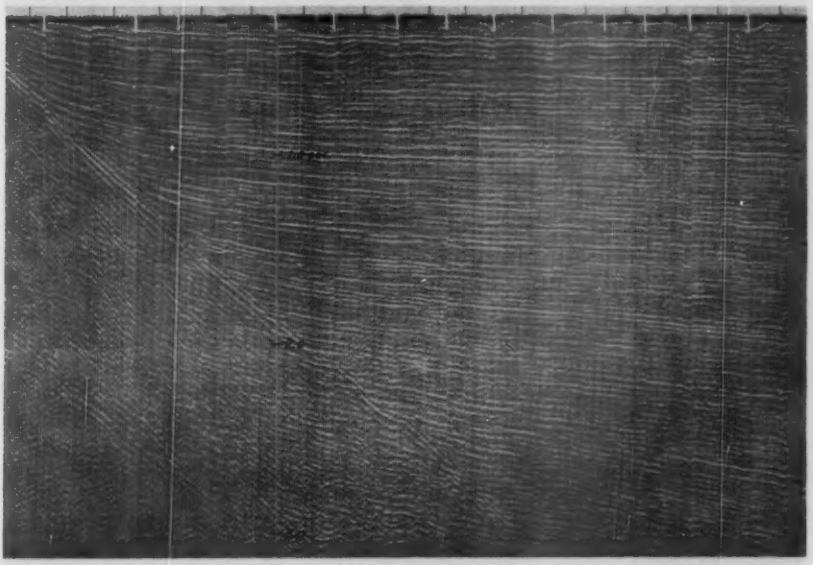

FIG. 1d. Portion of variable-density profile approaching flank of shallow salt dome. The steep dip arises from the near-vertical salt contact lying to the left of the section shown.

from ten seismic-information channels on 35-mm film to 24 channels on 70-mm film. Although the imperfections of the earlier seismic equipment tended to hamper acceptance of variable-density recording, the imperfections handicapped conventional recording as well, for which instrumentation was under continual development. The subsequent gradual improvements in seismic geophones, amplifier gain controls, and filters were applied to variable-density recording with increased fidelity and freedom from overloading and wave-training. Such improvements further advanced the versatility of variable-density re-recording techniques.

Meanwhile, it became increasingly clear that the variable-density records are of themselves visually significant. Contact prints of variable-density records, obtained with conventional field procedures and filters, were assembled side by

side to form "paste-up" profiles. Such improvised profiles were employed by Gulf over a period of years, and prompted the development of the present profile-printing system.

Experience with the Rieber apparatus, confirmed by additional gratifying experience with modernized equipment, led to the realization that full advantage of the variable-density presentation would be attained if the arrivals on all

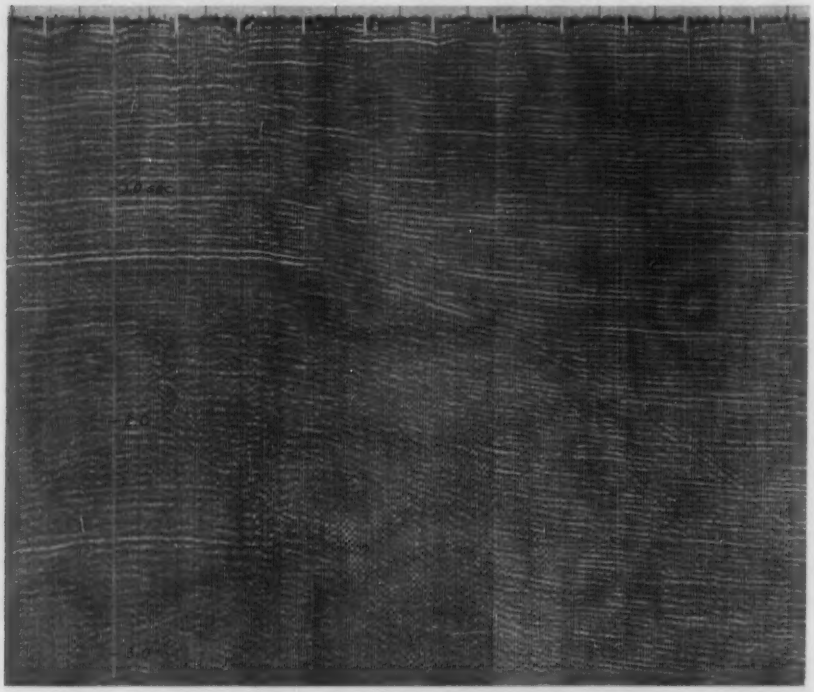

FIG. 1e. Portion of variable-density profile over salt dome. Note strong multiple reflections at about 2.5 seconds.

tracks comprising a complete profile were reduced to a uniform time basis, and were printed in a continuous sequence of tracks which could be easily copied photographically. The time basis was specifically chosen for the presentation, for events as displayed in time units are independent of time-depth curves which, if they are not more or less arbitrary, are subject to change even over short sections of a profile with acquisition of new time-depth information. Other attributes required of such a printing device were carefully considered and selected. The resulting printer thus logically stems from an extensive body of experience associated with the early art of phonographic reproduction of seismic data.

ADVANTAGES OF VARIABLE-DENSITY SEISMIC PROFILES

A seismic profile in variable-density rendition has important advantages for seismic interpretation. The channelization of seismic data is requisite for machine operations, and the inherent characteristics of the channels in variable-density form are particularly favorable for photographic production of seismic profiles. Unlike other channelized renditions, the width of the variable-density channel may be chosen without need for corresponding compensation of signal level. The horizontal scale of a profile may therefore be reduced without detracting from the visual clarity of seismic events; in fact, improvement usually results from such reduction. As a result, horizontal-to-vertical scale may be chosen as desired, within reasonable limits, for the best advantage of visual interpretation, subsurface geometry display, and offsetting techniques.

The pictorial result of the variable-density presentation is, as previously mentioned, strikingly like an actual section through the earth. Owing to the strong visual representation, the matching of a multiplicity of events is quickly resolved. On many profiles the correlations are immediately obvious. Pitfalls are obvious too, and may be avoided. If there are no correlatable events on a profile, this is also quickly evident.

In scanning across the tracks of a variable-density profile, the observer's eye automatically senses similarity of density levels and gradients, and thereby easily traces events having similar characteristics. This is in distinction to the need otherwise for carrying in the memory, or actually comparing relative amplitudes and wave shapes of limited portions of individual wavy-line traces. The trend of weak events may be followed across the variable-density tracks clearly, while on corresponding oscillographic traces the same events remain unnoticed. With oscillographic traces, the recording area is mostly featureless white paper, and in variable-amplitude modulation only the boundary demarking the white and black areas comprises the signal. In a variable-density presentation, the entire recording area is virtually filled with signal modulation, and therefore used at optimum efficiency.

With these distinct visual aids, the geophysicist may now apply a larger portion of his effort to reconstructing the geological conditions from which the profile picture arises.

VARIABLE-DENSITY RECORDER

Photographic film strips bearing variable-density tracks exposed in a special field recorder conveniently supply the original data from which the variable-density profile tracks are derived. The essential components of the field recorder comprise a film-transport mechanism driven by a synchronous motor, and a recording head. The record film, 70 mm in width, is positively driven through the recorder by means of sprocket perforations at a speed chosen to be five inches/second. Signal-modulated incandescent lamps illuminate small slit apertures close to the moving film. Standard amplifier channels supply the seismic signals through a set of lamp-drive channels.

The incandescent recording lamps are employed essentially as they were devised by Rieber. As recording elements, these tiny lamps have the advantage of simplicity, and mount compactly in a small housing. A dc lamp-bias current, which supplies the normal, no-signal illumination level, produces a moderate gray density on the developed record track. The steady bias current, passing through the secondary of a coupling transformer, is modulated by the seismic signal. The denser portions of the record track thus correspond to higher lamp currents, and vice versa. Compensation for the falling frequency response of the lamp with increasing signal frequency is provided in each lamp-drive channel, although the inherent rapid fall-off is permissible above about 100 cps. The slit apertures in the recording head are in line on 1/12-inch centers. Between the two rows of sprocket holes in the 70-mm film there are 27 variable-density tracks, of which 24 are for seismic-information signals and one each for a 100-cps timing signal, a time-break signal, and an up-hole, or shot-point geophone signal.

The variable-density recorder is operated simultaneously with a standard oscillographic recorder in the usual field installation. The one-hundred-foot lengths of exposed 70-mm film, comprising an automatically numbered sequence of individual records, are developed at periodic intervals in the field office.

BASIC FUNCTIONS OF THE PRINTER

In transferring the variable-density record tracks to variable-density profile tracks, the profile printer (Fig. 2) performs data-adjustment and photographic steps simultaneously. The successive variable-density tracks of the records of a traverse are contact printed in turn across the width of a continuous sheet of photographic film. In exposing a record track, a printing head moves across the profile film at a steady rate and, by means of an illuminated slit, transfers each event on the record track to the profile film. After completion of the exposure of each track, a shutter cuts off the exposing light and the printing head returns to the opposite end of the record in preparation for the next scanning cycle. Meanwhile the record advances to the next track, and the profile film advances to a new profile-track position ready for exposure during the next traverse of the printing head.

Prior to the printing exposure of a particular track, the entire record is displaced lengthwise by the amount of the surface correction appropriate to that track. The record-displacement mechanism is automatically adjusted for each record track in accord with surface-correction data supplied by a punched card. In addition, a record is gradually shifted in time during the printing exposure so that successive events on a record track are printed with appropriately varied time displacements. Such displacements, automatically computed by the mechanism, are corrections required to reduce slant-path travel times to vertical-path travel times. The computations are based on information supplied by a second punched card and by a cam shaped to represent wave-front velocity data suitable for the prospecting area. The developed film, from which paper copies

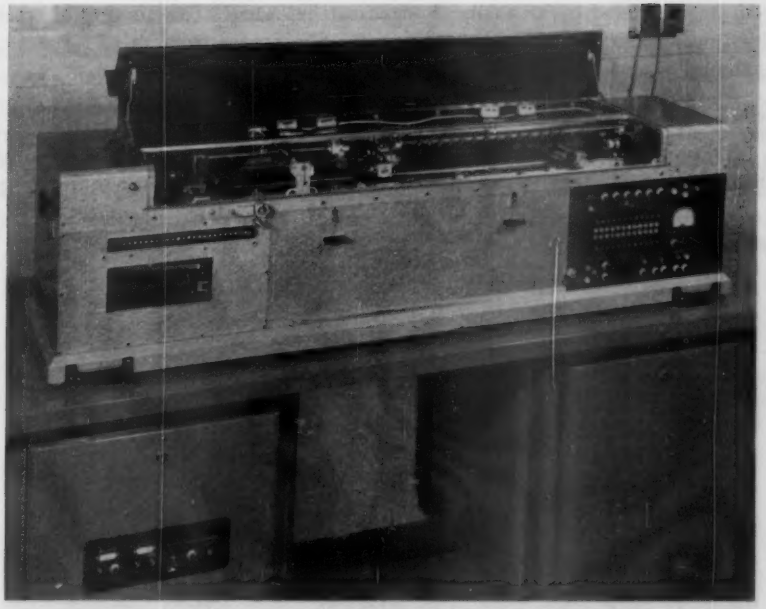

FIG. 2. Profile printer assembly. Light-tight cover is closed when printer is in operation.

are easily made, is a section profile bearing the appropriately time-altered representation of the original variable-density tracks.

BASIC COMPONENTS OF THE PRINTER

The printer comprises several basic components, including a profile-film transport magazine, a frame to hold the record and maintain alignment of the tracks, a printing head comprising a light source, shutter, and printing aperture, mechanisms to drive the printing-head carriage assembly and to displace the record according to the desired time corrections, and control devices directing and synchronizing the various operations.

Profile-Film Magazine

The profile-film magazine, shown on a transporting stand in Fig. 3, comprises a supply roll, take-up roll, dc motor, drive mechanism, and light traps. An important component is a "printing roller" around which the profile film passes emulsion side out in traversing the magazine. The film lies smoothly and tightly across the upper side of the roller upon which each record track is exposed. The profile film is 20 inches wide, and is supplied on rolls in 100-foot lengths. The 20-inch width allows about 3.8 seconds of recording time at the chosen record speed of five inches/second. The film is periodically driven forward in increments

accurately metered by an easily changed ratchet wheel. The number of tracks which may be printed on an inch of profile film ranges from 12 to a practical maximum of about 24.

Record Frame

The record frame, a flat plate containing a slotted, rectangular opening into which the variable-density record is clamped, holds the record close to the upper-

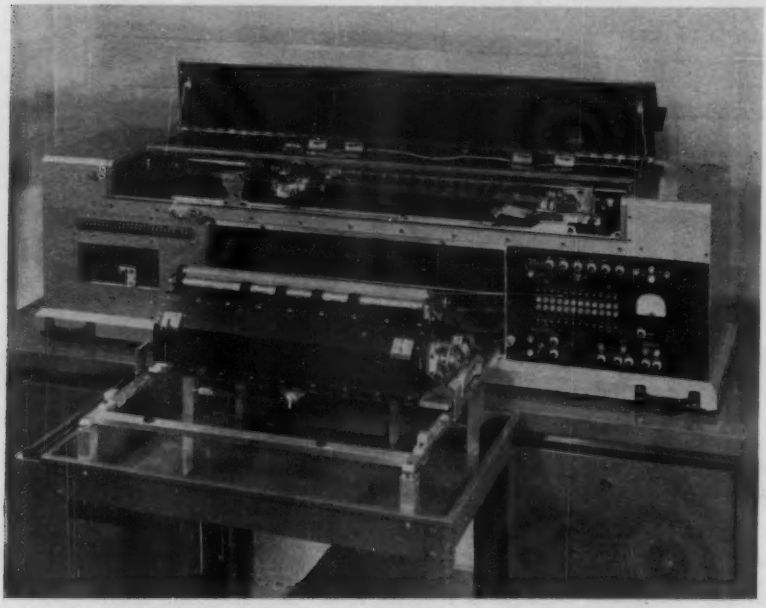

FIG. 3. Profile printer with profile-film magazine on a transporting stand. Mechanism is in position for change of a record.

most side of the printing roller. The left-hand end of a record loaded in the frame, and a portion of the printing roller, may be seen in Fig. 4. Indexes are arranged at intervals along the length of the record to aid in track alignment when the frame is in a forward, record-loading position. Periodically, as a record is reproduced, the record frame advances transversely by increments which correspond to the standard record-track spacing. Record frame advancement from track to track may be in either direction.

Printing Head

The exposing light source within the printing-head housing (Fig. 4) is a small incandescent lamp illuminated by steady dc current. The lamp current may be

set to a value suitable for record-track exposure by a rheostat mounted on the main control panel. The operator may monitor the lamp intensity by the indication of a panel-mounted microammeter which is connected to a photovoltaic cell within the lamp housing. A rotary shutter in the housing permits exposure of the profile film at the proper time in the operating cycle. During the cycle, a synchronous motor drives the printing head along the printing roller at an essentially uniform rate. A replaceable mask mounted at the base of the lamp housing transmits the exposing light through a suitably shaped slit about one-eighth inch in length. Two small rollers, one on each side of the housing, hold the mask as

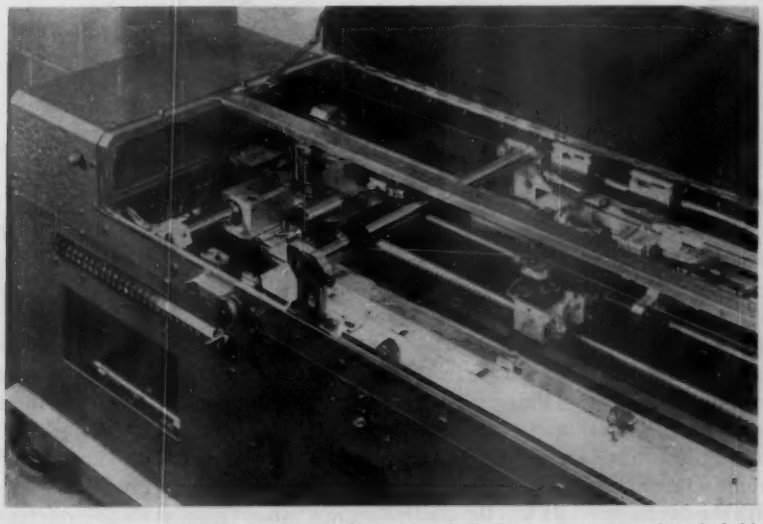

FIG. 4. Left-hand end of chassis. The printing head periodically traverses a record track, held in alignment by the record frame, and exposes the profile film.

close as practicable to the record, and also serve to press the record lightly against the profile film to assure contact over the exposure area.

Main Plate

In order to effect the time corrections previously mentioned, the record frame must be continuously movable in the lengthwise, or longitudinal direction of the record tracks. To satisfy this requirement, a second flat plate, termed the "main plate," carries the record frame and much of the associated mechanism as a unit and is supported so as to move lengthwise within the chassis. Fig. 5 shows the relationship between these parts and the profile film passing over the printing roller. The main plate is urged rightward by a spring, but restrained by a small flexible cord, termed the "main-plate cord," whose function is to control the main-plate position with respect to the profile film.

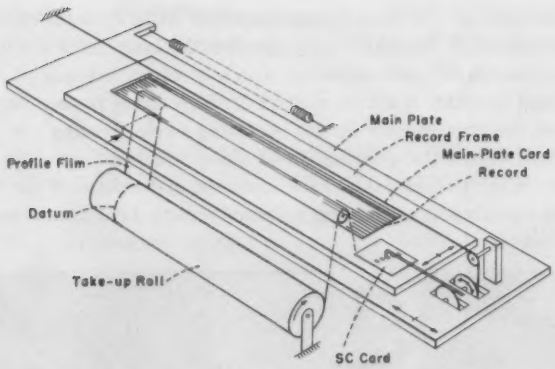

FIG. 5. Main plate, record frame, profile film, main-plate cord, and associated parts effecting surface-correction displacement of a record track with respect to the profile film.

Profile-Datum Indexes

Quantitative correction of seismic-arrival time requires consistent use of a time-reference system for record-track displacement throughout all steps in the printing of a profile. The time reference employed in the printer is the profile datum, which is drawn as a permanent reference on the profile film. Near the left-hand end of the printing roller, a blunt scriber presses against the profile film and embosses a narrow groove in the film emulsion as the film passes over the printing roller. The indexing groove is visible when the case is open for adjustments; and, owing to the pressure sensitivity of the emulsion, the groove is transformed into a dark line upon development, and becomes the datum of the profile section (Fig. 1a). The main plate in turn carries an index which is aligned with the datum groove when the controlling mechanism is set at its zero reference. Figure 5 shows the main-plate index as an arrow lying on the plate. The time break of each record is adjusted to coincide with this index before the record is clamped in the record frame.

SURFACE CORRECTION

The need for seismic-arrival time correction arises in part, as is well known, from the departure of geophone and shotpoint elevations from the datum elevation, the net time lost by wave-front traversal of the weathered layers, and so on. Corrections of this nature may be combined into a time value to be applied along the entire length of a record track. The value of the combined correction is different in general for each track. Before a profile is printed, such surface corrections, abbreviated "*SC*," are calculated by customary methods with reference to a selected datum. The *SC* data are stored on punched cards. Prior to the printing of each record track, the automatic mechanism displaces the main plate, and hence the record track, according to the *SC* card correction

value for that track; and during the printing of the track the *SC* displacement remains constant.

Main-Plate Displacement

For appropriate surface-correction displacement of the main plate, the mechanism has only to adjust the effective length of the main-plate cord which restrains rightward main-plate motion (Fig. 5). A small carriage, which carries an electrically conducting stylus, is located near the right-hand end of the main plate. The stylus overhangs an extension of the record frame (Fig. 6) on which a

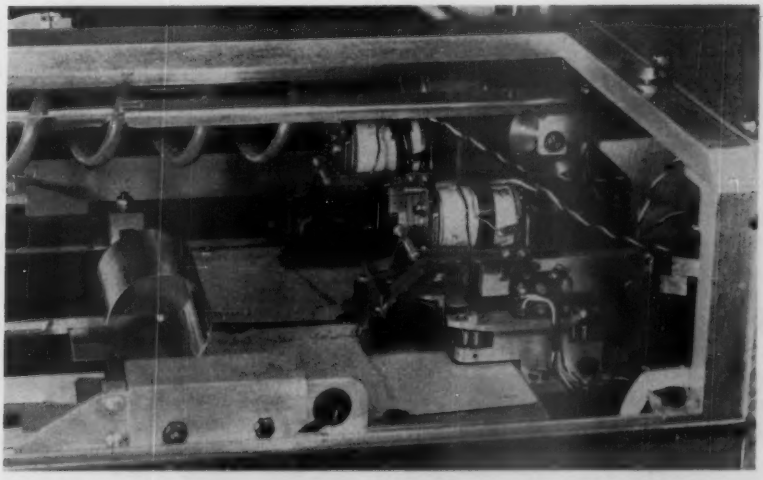

FIG. 6. Right-hand end of chassis. The punched cards, mounted on the record frame, are scanned by similar stylus mechanisms.

punched card bearing the *SC* data is accurately positioned. Periodically during the printing operation, the stylus bears upon the card, and sliding over the non-conducting surface, scans the card for a punched hole. A motor drives the *SC* carriage and simultaneously winds up the main-plate cord (Fig. 5). When the tip of the stylus falls through the hole and contacts a grounded plate beneath the card, the motor immediately stops rotation. The main plate, the record frame, and the record then occupy the desired *SC* position. At this point in printer operation, the printing head travels along the printing roller and prints the corresponding record track.

Surface-Correction Check

The position of the main plate relative to the datum at the time of printing of each track is permanently recorded on the profile film. As each record track is

printed the exposure is interrupted over a short segment near the lower end of the track. The unexposed segments monitor the *SC* mechanism, and when compared with reflection-event alignments, the band of segments across the lower edge of the profile (Fig. 1a) shows the effectiveness and adequacy of the applied surface corrections.

Punched SC Cards

After surface-correction data are prepared, an *SC* card for each record is conveniently punched in a special device (Fig. 7), which will be described later.

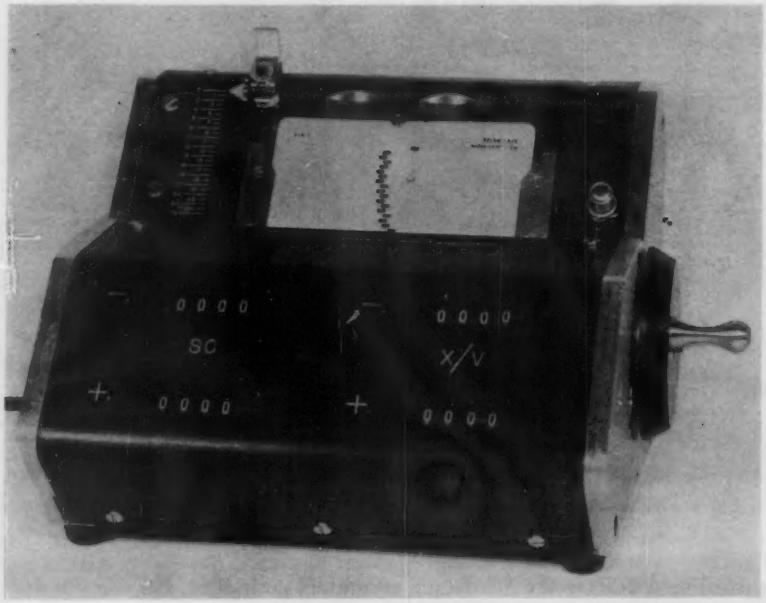

FIG. 7. Card punch. The counters are set by the hand crank to indicate desired hole displacements. The uppermost hole was punched with counters set at zero.

The punched holes are located crosswise on the card at 1/12-inch intervals, corresponding to the standard record-track spacing. Lengthwise on the card the holes correspond in position to the magnitude of the surface correction relative to a "zero" hole position near the center of the card. One hole only is punched for each record track. The punched card and the printer mechanism provide for surface corrections of ± 280 milliseconds.

VARIABLE CORRECTION

Corrections for seismic arrivals comprise not only the constant values previously considered, but also values which vary with observed travel time. The

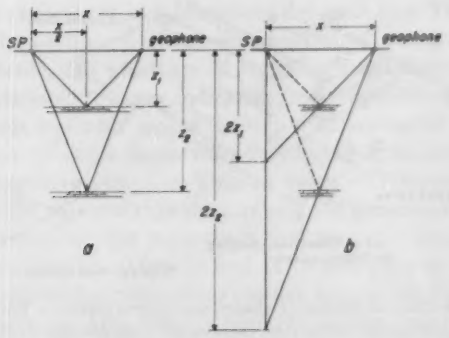

FIG. 8a. Reflection travel paths. Beds are horizontal; wave-front velocity is constant.
FIG. 8b. Shotpoint-image construction for the reflection travel paths of Figure 8a.

variable corrections, which are commonly termed stepout, or angularity corrections, arise from the spacing of geophones at discrete distances from the shotpoint. During the printing operation, arrival times on a variable-density track are corrected for the effects of varying path geometry and varying wave-front velocity.

Fig. 8a shows the well-known travel-path geometry for seismic events reflected from beds at depths z_1 and z_2. Fig. 8b shows the equivalent reflection paths as continuous lines, and in this diagram the image of the shotpoint as formed by each reflecting bed is considered to be the actual source. The correction mechanism of the printer relies upon the characteristics of the shotpoint-image construction, and upon the assumption that, although average wave-front

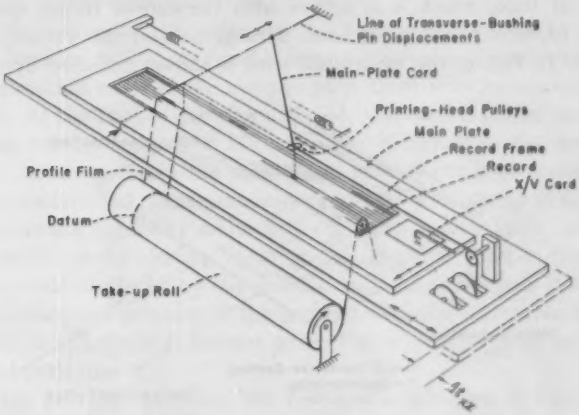

FIG. 9. Mechanism effecting variable-correction displacements Δl_{xz}. Small pulleys above the illuminated printing-head slit move parallel to the long roller; the main-plate cord, deflected by the pulleys, gradually displaces the record track with respect to the profile film.

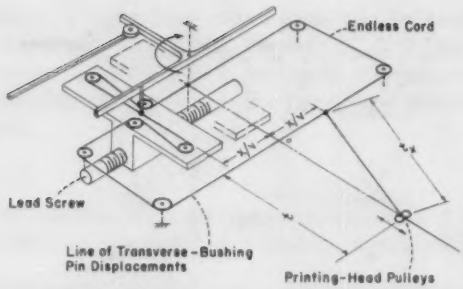

FIG. 10. Velocity-function mechanism (T-shaped arm in zero position). Rotation of lead screw displaces termination point of the main-plate cord.

velocity generally increases with increase in vertical-path time, the average wavefront velocity is nevertheless uniform throughout the medium for any particular value of vertical-path time. Thus it is assumed that reflection paths are straight lines. It is further assumed that all reflecting beds are horizontal, for an assumption otherwise is not justifiable prior to the printing of a profile.

In the process of applying variable time corrections to variable-density tracks, a travel-path diagram, such as one of those in Fig. 8b, is considered as converted into a travel-time diagram by division of component distances by a velocity. The resulting times are represented by the mechanical parts of the printer mechanism, in which dimensions of length are analogs of time. The diagrams relating the actual paths, the corresponding time values, and the dimensions representing the time values, are geometrically similar. In the following discussion, a dimension of five inches in the printer mechanism corresponds to one second of time, which is in accord with the chosen record speed.

Figs. 9, 10, and 11 show the basic arrangement of the variable-correction mechanisms. In Fig. 9, the main-plate cord is shown deflected by one of two

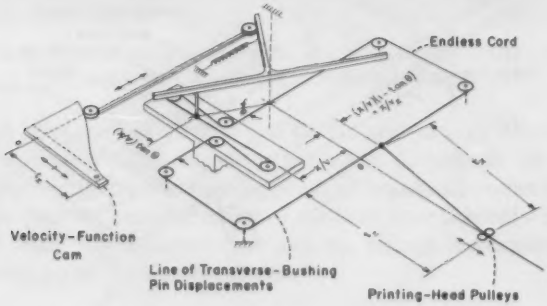

FIG. 11. Velocity-function mechanism (T-shaped arm rotated through angle θ). By rotating the arm, the cam (actually cylindrical) modifies termination point of the main-plate cord.

small pulleys and terminated at a horizontal dot-dash line. The exposing slit of the printing head and the associated pulleys, two of which are employed for symmetry in operation and which are of negligibly small diameter, are mounted on the carriage assembly and are indicated in vertical alignment by a dashed line. As the carriage assembly moves through a succession of positions relative to the dot-dash line, which represents the datum, the main plate moves through a succession of correction positions. Thus an event on a record track is in corrected position at the moment that the exposing slit passes across the event and prints it on the profile film. The main-plate cord geometry is also shown in association with the mechanism (Figs. 10 and 11) whose purpose is to control the main-plate cord termination point along the line representing the datum.

The mechanical parts of the velocity-function mechanism are shown schematically in Fig. 10 in the position they occupy for the special case of unchanging wave-front velocity. A reflection event whose slant-path time is indicated as t_x would be printed, as the carriage assembly traverses the record track, at the distance t from the datum. The distance t is related to the slant-path distance t_x by the displacement x/v of the main-plate cord termination point. In the parameter x/v, the quantity x is the shotpoint-to-geophone distance for a specified record track and the quantity v is in velocity units. If, however, the average wave-front velocity changes with vertical-path time, the mechanical parts of the mechanism occupy positions as shown schematically in Figure 11. In the general case, the main-plate cord termination point should vary during the printing of a record track and, specifically, should have the varying displacement x/v_z, as shown. The value v_z is defined as the average wave-front velocity in the medium, and varies with vertical-path time t_z. As shown in Figure 11, an event whose arrival time is t_x is printed, when account is taken of changing average wave-front velocity, at the distance t_z from the datum.

In practice, values of the parameter x/v for the various tracks of a record are punched into an X/V card. For this purpose the value of v may be considered to be the minimum value of the average wave-front velocity v_z encountered in the medium. At the time of printing a record, this card is placed on the record frame beside the corresponding *SC* card (Fig. 6). Prior to the printing of a record track, a dc motor in the mechanism rotates the lead screw (Fig. 10). and through a selsyn link, simultaneously causes the X/V stylus to scan the card for the appropriate hole. The main-plate cord termination point, which in the printer is the axis of the pin in a bushing (Fig. 4) which slides on the transverse rod, is meanwhile displaced by the endless cord. After the hole is located and during the subsequent printing of the record track, the transverse-bushing pin displacement is the desired amount x/v_z (Fig. 11) and varies appropriately with vertical-path time t_z.

During the printing operation, the *T*-shaped arm shown in Figs. 10 and 11 rotates through an angle θ. The cam on the left-hand side of the diagram is shaped to impart rotation to the arm such that $\tan\theta = 1 - v/v_z$, in which v/v_z is a

function of t_s, readily determined from a conventional time-depth curve for a prospecting area. It may be noted that the sliding attachment of the endless cord to the arm, together with the pulley arrangement, subtracts the quantity $(x/v)\tan\theta$ from the displacement x/v in Fig. 10. The resulting displacement of the main-plate cord termination point in Fig. 11 is $(x/v)(1-\tan\theta)$. The angle θ may be eliminated from this expression by substitution of $\tan\theta = 1 - v/v_s$. Thus it follows that the net transverse-bushing displacement $(x/v)(1-\tan\theta) = (x/v)(1-1+v/v_s) = (x/v)(v/v_s) = x/v_s$, which is the desired function of t_s. As the

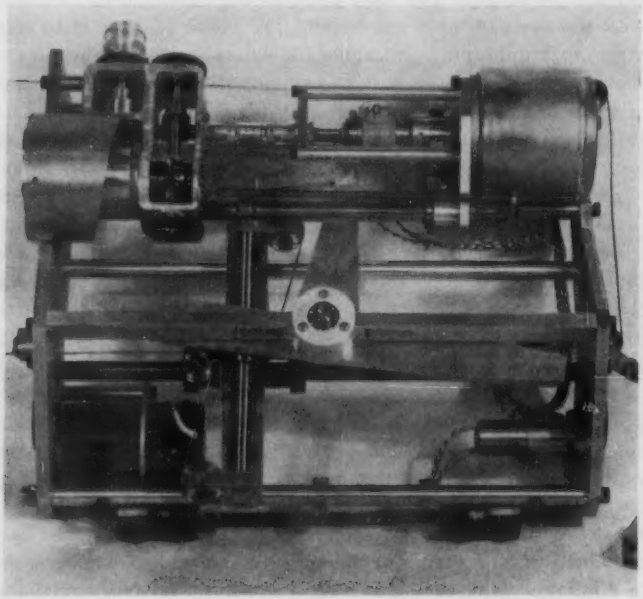

FIG. 12. Velocity-function mechanism. Lead-screw driving motor, lower right; selsyn transmitter, lower left; cylindrical cam, upper left; printing-head carriage driving motor, upper right.

result of the operation of the mechanism, record-track events which are printed on the profile film at vertical-path times t_s are displaced by the quantity $\Delta t_{ss} = t_x - t_s$ (Figs. 9 and 11), in which t_x and t_s are related by the varying quantity x/v_s. The bushing-displacement mechanism (Fig. 12) is housed in a compartment in the left-hand side of the printer chassis.

Velocity-Function Cam

The photograph of Fig. 12 shows the velocity-function cam, which is readily replaceable, as a thin-walled, hollow cylinder. The cam is rotated through gearing by the synchronous motor which simultaneously drives the printing

head. A suitably calculated family of cams obviates the construction of a specific cam for each time-depth curve, since one cam will serve for those cases in which the ratio v/v_s is substantially the same function of t_s. In rare instances the average wave-front velocity may decrease with time so that the ratio v/v_s may increase through a certain range of values of t_s. The cam mechanism as designed permits representation of such a function, or in fact any function of v/v_s with respect to t_s, provided only that the value of v is chosen to keep the ratio v/v_s less than unity and greater than one-half.

Punched X/V Cards

The X/V cards are similar to the *SC* cards previously described, and holes representing values of the parameter x/v are punched by use of the same card punch (Fig. 7). Inasmuch as a spread of geophones may span the shotpoint, or lie entirely on one side or the other, it is convenient to assign positive or negative signs to values of x/v, and to punch the holes with respect to a zero-reference hole position. Holes thus invariably fall in echelon alignment and are generally spaced uniformly, corresponding to the uniform spacing of geophone stations for continuous center-point control. A single X/V card ordinarily serves for the records for which the geophones and shotpoints remain in fixed geometrical relationship along a profile. The punched card and the printer mechanism provide for x/v values somewhat greater than ± 900 milliseconds. By the use of punched cards, the printer mechanism easily handles corrections for irregular spreads, offset shotpoints, and broadside shots in normal routine.

Datum Adjustment

The variable corrections Δt_{xs} are calculated by the printer mechanism em ploying time values which are referred to the selected datum. In cases for which the datum elevation departs appreciably from the surface elevation, it may be desirable, however, for the mechanism to calculate the Δt_{xs} corrections with respect to the surface. The proper printer geometry is provided by a "datum adjustment" by which the printing head is displaced relative to the small pulleys (Fig. 9) on the carriage assembly. The amount of printing-head displacement, which is constant for a record, corresponds to that part of the surface correction comprising the total wave-front travel time between the average surface elevation over which the spread of geophones extends and the elevation of the selected datum. By this adjustment, the exposing slit is positioned with respect to the surface, while the pulleys are positioned as before with respect to the datum. Thus the corrections Δt_{xs} are applied to appropriate portions of the record track during the printing cycle. The range of adjustment is ± 200 milliseconds.

CARD PUNCH

The card punch (Fig. 7) comprises an electrically operated punch assembly and card transport and escapement mechanism. The punch assembly rides on a

manually rotated lead screw. Digital counters, representing positive and negative SC and x/v parameter values, are geared to the lead screw. The digital number appearing in the proper counter window represents in milliseconds the magnitude of the hole displacement from zero. A push-button switch actuates the punch and the card-transport escapement.

PRINTER ASSEMBLY

The printer mechanism, which is designed to operate in a normally lighted room, rests on a console-type table (Figs. 2 and 3), and in the left and right pedestals of the console the power supply and the control circuits are mounted on plug-in shelves. Printer controls comprise a main and a subsidiary control panel, various limit and override switches, and the two stylus assemblies. The main control panel provides means for preselection of various types of operation. A set of 24 toggle switches permits presetting of specific printing cycles on which special printing functions are desired, and these functions are initiated at the appropriate time by use of one of a set of push-button switches. The main circuits together with interlock and check circuits require about one hundred conventional relays, which function individually, in sequence, or in combination to provide essentially automatic operation of the printer. Indicator lamps show at all times the progress of the printing and related information.

OPERATION OF PRINTER

Prior to the running of a profile, the operator checks zero adjustments; equips the film magazine with the ratchet wheel giving desired increments of profile-film advancement; inserts the film magazine into the printer (Fig. 3); inserts an aperture mask in the printing head with an exposing slit of appropriate width; installs a suitable velocity-function cam; arranges for the record frame to step from track to track in the desired direction; sets a select switch for the form of printing desired; and performs the routine operations which normally precede the printing of a record.

When a record is installed, the operator carefully aligns the record with the indexes previously discussed and clamps the record; installs the corresponding SC card; replaces the X/V card if a change in card is required by this record; sets the datum adjustment as required; closes the cover of the case; places the record frame into operating position; sets appropriate control-panel switches; and places a standby switch in run position. Providing interlock conditions are satisfied, printing begins for the record, and unless controls are set for special functions, printing of the 24 record tracks continues in uninterrupted sequence.

Typical Printing Cycle

At the start of a typical printing cycle, the printing carriage assembly, including the printing head and the small pulleys located above the exposing slit, moves rightward (Fig. 4) from the standby, or left-limit position. During the

rightward motion, the printing-head shutter is closed. The *SC* stylus and the *X/V* stylus scan their respective punched cards for the holes appropriate to the track to be printed, and the film-magazine mechanism advances the profile film the required increment. If during the transit interval of about two seconds these circuits have completed their functions, the carriage stops at the right-limit position and immediately moves leftward. However, if any of the functions are not completed, the carriage dwells at the right-limit position until completion.

As the carriage assembly starts to move leftward, the printing-head shutter opens. The printing exposure takes place during the leftward traverse. For this direction of carriage travel the main-plate motion is smooth; and the Δt_{z_1} correction displacement imparted by the main-plate cord starts from a small value and increases gradually. The leftward traverse is completed in approximately two seconds. The carriage assembly then momentarily dwells at the left-limit position, the shutter closes and the record frame advances to the adjacent record track. The corresponding holes in the *SC* card and the *X/V* card automatically align with the *SC* stylus and the *X/V* stylus. The carriage assembly then moves rightward, repeating the steps of the preceding cycle.

Upon completion of the final track, the carriage assembly stops in the left-limit position, and the operator receives a visual and audible signal that the running of the record is completed. The operator then changes the record, performing the operations described previously. The basic elapsed time for the running of a 24-track record, including the change of record, is about three minutes. The time may be greater than indicated when unusual printing forms or numerous special printing functions, which will be discussed later, are employed. On an average profile, however, an operator may print from fifteen to twenty 24-track records in an hour.

Auxiliary Functions During a Printing Cycle

At the upper edge of the completed profile (Fig. 1a) a series of notches, which are actually shortened tracks, demark the span of the tracks of each record. The height of the first printed track of each newly loaded record is automatically made slightly less than normal. In this case special circuits terminate the exposure somewhat earlier as the carriage assembly concludes its leftward traverse.

The normal upper limit of the tracks reproduced on the profile film is determined by the left limit of carriage-assembly travel. For large values of the parameter x/v, leftward travel of the carriage assembly is limited by a switch mounted on the carriage assembly near the small pulleys (Fig. 4). This switch stops leftward travel whenever the angle of the main-plate cord, and therefore the effective reflection angle of the wave path, equals an arbitrarily fixed angle of approximately 45°. This limitation of left-limit position is imposed for mechanical reasons, and also because beyond such an angle, the record-track events are generally not reflections, but refractions.

The *X/V* stylus and the *SC* stylus are lowered upon their punched cards

only during the hole-seeking, or scanning direction of motion. Since holes punched in the *X/V* card are invariably in echelon alignment, the *X/V* stylus scans quickly to the next hole. Holes punched in the *SC* card, however, are generally displaced longitudinally from one another by increments in either direction. Since these increments are generally short, the *SC* stylus moves forward a relatively short distance ahead of its previous stopping point before seeking the adjacent hole. By avoiding a complete scan of the card, which would require an unreasonable length of time, the *SC* stylus does not hold up operation of the printer. In the event that no contact is made by the *SC* stylus upon reaching the end of the range of motion in the scanning direction, the stylus moves ahead to scan the card from the opposite side.

The printer circuits sense that a trouble condition has arisen if the *X/V* stylus fails to find a hole, if the *SC* stylus completely scans its card without finding a hole, or if the magazine runs out of film. In any of these cases, the trouble condition is evidenced by the intermittent sounding of a buzzer and flashing of the indicator lamp which is otherwise lighted steadily when the circuit in question is in normal operation. Also, the printing-head carriage assembly automatically moves to the left-limit position with the shutter closed so that the profile film is not exposed. The printer thereupon ceases automatic operation, and the number of the track in question is displayed by a lighted indicator lamp. The operator may find that the trouble is trivial, for example, that a hole is missing in a punched card. After remedying the condition, the operator may restart printing, and the circuits provide for continuation of printing of tracks in uninterrupted progression on the profile film.

At any point during the printing of a record, the operator may temporarily suspend printing by use of a "pause" push button, following which the carriage assembly stops at the next succeeding limit position. Operation is resumed by the pushing of a "resume" push button, and printing continues from the point of suspension, the automatic sequence of functions being undisturbed by the interruption.

Special Printing Functions

The primary task of the printer is to reproduce record tracks in succession on the profile film, and it might appear that it is only necessary to reproduce the tracks of each record one after the other. However, the conditions under which records are made in the field, and the purposes for which the profiles are later employed, require provision for special printing operations. For example, if on a profile traverse one or more center-point locations are common to tracks of adjacent records, one of each pair of duplicated tracks should be eliminated. On the other hand, an excessive number of consecutive gaps in center-point locations should be represented by corresponding blank spaces on the profile film in order to maintain horizontal scale.

Such contingencies are handled during the printing of a record by use of the previously mentioned set of 24 toggle switches of the main control panel. When printing progresses to the track for which one of these switches is preset, the printer halts, a lamp and buzzer calls the attention of the operator, and a lighted translucent track-number disc adjoining the switch in question identifies the record track. The operator initiates the special printing function for that track by operation of one of several push buttons. Following the use of the special-function circuits, printing resumes automatically when the operator returns the present toggle switch to normal position.

One of the special functions which may be required is the skipping of a record track. For the skipping function, the record frame advances the record from the track in question to the next adjacent track as the carriage assembly dwells in in the left-limit position. Another function is the repetitive printing of a record track, which may be repeated in succession as many times as desired. By use of another push button, a record track may be omitted from the profile, and the position it would have occupied remains blank. For this function the record frame advances the record from the track in question to the next adjacent track, and the profile film advances one increment. In addition, a succession of blank profile-film increments may be inserted between specified record tracks. This function is accomplished by push-button control of profile-film advancement prior to resumption of printing, and printing resumes with tracks following in normal sequence.

Forms of Printing

The form of printing normally employed is "regular," in that each record track is printed one time only. In another form of printing, termed "pairs," each record track is printed twice. An advantage of the track duplication of pairs printing is that the horizontal scale of the profile may be doubled. Six record tracks may, for instance, be printed on an inch of profile film instead of the usual minimum of 12.

A third form of printing, termed "mix," is a variable-density analogy to the method of compositing variable-amplitude traces in field equipment. Unlike compositing in field equipment, however, both fixed and variable corrections are applied to each event prior to compositing. The mix form of printing is accomplished by double exposure of the profile tracks, and the operator proportionately reduces the intensity of the printing lamp. The mix circuits also automatically mix the comparable tracks of adjacent records. For special functions with pairs and mix printing, the operator employs the push-button routine as described previously for the regular form of printing. In some cases in mix printing it is desirable to print an individual track two times in the same profile-film position in order to maintain the density level on the processed film, a function which is also provided for by push-button control.

The forms of printing described are readily accomplished by the printer and,

together with the special functions which cover the range of cases which arise in practice, adequately provide the versatility which must be built into the device for the production of consistently printed profiles.

CONCLUSIONS

The profile printer produces a type of seismic-data presentation which on one hand compresses the great mass of information of a seismic traverse into a compact relationship which retains all detail originally recorded. On the other hand, the presentation displays all inherent information content of the data at a glance. The variable-density form of presentation of the seismic information is basic to this accomplishment. The time-corrected profile tracks assure reliable correlation and interpretation. Choice of horizontal scale, correction parameters, and special printing functions, as outlined, further the versatility of the system. By their current employment in seismic exploration programs, the time-corrected, variable-density profiles are daily proving their utility.

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A PROBLEM IN THE ANALYSIS OF GEOPHYSICAL DATA*

FRASER GRANT†

ABSTRACT

The problem is to analyze mapped data into components which may be termed "trend" and "residual." The approach used is polynomial fitting by least squares, following the method of DeLury when the data are evenly distributed (or sampled), and of Kendall when they are not. The DeLury method, however, is extended somewhat in scope to include missing values. A number of statistical tests are discussed which should assist in determining the optimum amount of complexity to ascribe to "trend." The attitude taken throughout this paper is unbiased in the sense that positive and negative residuals are held *a priori* to be equally likely. An example is given of the regional correction of a gravity survey designed to explore for sulphides near Val d'Or, Quebec. In conclusion, a brief discussion is given of the advantages of polynomial fitting over smoothing and "gridding" methods from the point of view of labour and costs.

INTRODUCTION

The problem discussed in this paper is the analysis of mapped geophysical data into components which may properly be termed "trend" and "residual." One obvious application of this concept is the regional correction of gravity or magnetic field data; but it is the writer's opinion that equally valid uses may be found in seismic and other survey problems as well as in stratigraphy. Any instance in which one wishes either to remove the trend or to obtain it in a functional form from a mapped distribution of data is a legitimate application for the methods discussed under this title.

This paper was written with two objects in mind. The first was to suggest a particular type of solution to the problem described above, and the second was to explore some of the uses of statistical methods in making the solution an optimum one. The first of these tasks, happily, already has been performed in this journal by Oldham and Sutherland (1955); for this writer shares the opinion that polynomials, with their great flexibility and their special computational advantages are among the best of existing mathematical tools for analysing geophysical data. At the risk of a small loss in economy, however, the principal points of the DeLury method of polynomial fitting will be restated here in order to clarify a number of questions relating to statistical tests. The number of different tests proposed in this paper is rather large, but it should not be necessary (nor perhaps even desirable) to use every one of them in each problem. The proper combination will depend upon the nature of the data and upon the experience of the interpreter, and no doubt both will be highly variable. Some are applied to the example in this paper merely for purposes of illustration.

The word "regional," either noun or adjective, will be avoided whenever possible from here onward. It is one of those unfortunate terms in the jargon of geophysics that has become irremediably equivocal by usage. Expressions such

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as "regional effect," "regional background," and so on are encountered in the literature and in the profession with such a wide variety of implied connotations —some physical, some geological, others even purely economic—that any exact general meaning dissolves upon inspection into a nebula of utter confusion. The word "trend" in this general context is more satisfactory, since it has a more precise meaning and—most importantly—is capable in special applications of a fairly rigorous definition. Whether or not the trend or any part of it, once determined, shall be identified with the "regional effect" is properly a matter for the individual to decide for himself in the light of his interpretation of the true meaning of the term.

THEORY

The method consists in fitting a polynomial to the data up to the point where the trend is adequately specified. It is an important feature of the DeLury method that the degree of the polynomial that gives the most efficient estimate of trend is determined from the data, and is not preassigned arbitrarily. Obviously the success of this approach depends upon the validity of the assumption that whatever trend exists can adequately be described by a polynomial of low order. With most geophysical data, this assumption should rarely fail.[1]

To state the problem, let us specify the set of observations with the symbol T_i. T_i represents a given set of physical measurements and as such it acquires actual values only at the set of points (x_i, y_i) at which measurements have been taken, and has no meaning elsewhere. T may represent for example, magnetic intensity, Bouguer gravity, seismic wave velocity, depth to a lithologic boundary, or in fact anything that can be measured numerically over an area.

We next suppose that there exists a function $\tau(x, y)$ that describes the trend behaviour of the field or measured quantity, quite independently of any experiment. Finally, we seek to determine from T_i the function $t(x, y)$ that provides the best possible estimate of τ, and which is unbiased in the sense that it tends to τ as the number of observations increases indefinitely. It is assumed that T differs from t at each point of measurement by a residual that varies from point to point in an unpredictable way, but whose most probable value over the entire set of observations is zero.

In symbols, $T_i = t_i + \epsilon_i$, where $t_i \equiv t(x_i, y_i)$ is an estimate of trend and ϵ_i is a residual that represents small-scale fluctuations, plus actually random disturbances that may be due, for example, to reading error or to near-surface conditions. In this paper, two particular assumptions are made about the structure of the residual field $\epsilon(x, y)$:

1) The residuals are uncorrelated, and
2) the average value of ϵ_i over the entire set of observations is zero.

[1] Exceptions are those data which contain discontinuities, such as seismic reflection time data across a fault.

The first of these assumptions is usually fulfilled when the observations are independent of one another. Strictly speaking, however, non-correlation implies that the covariance of ϵ_i and ϵ_j is zero, $i \neq j$; whereas in practice the small-scale fluctuations in T, which may introduce correlation into ϵ within local groups of stations, tend to produce a small but positive covariance. Tacitly, we ease this constraint somewhat by assuming that, taken over the entire set of observations, this covariance is very small with respect to that of the trend terms and may be neglected.

The postulate that ϵ_i has a zero mean is the expression of a particular attitude of mind toward the residuals *prior* to the experiment, in which positive and negative values are held to be equally likely. In adopting this attitude, it is supposed not only that the method of observation is free from bias or from systematic error, but also that the nature of the subsurface is such that positive and negative local disturbances have about the same probability of occurrence. This might be termed the attitude of least prejudice, but it is not often unconditionally tenable. As an example, in fitting a trend to gravity data taken on the Gulf Coast where salt structures are known to exist, one might wish deliberately to bias the trend so as to favour the production of negative residuals. Attitudes of this kind are not infrequent, and when they are founded upon direct geological experience they represent legitimate additional information about the problem. If such feelings can be stated sufficiently precisely that the prior probability distribution for the residuals can be formulated, then the trend can be determined to any assigned level of *posterior* probability, or probability as modified by the result of the experiment. Unfortunately, attitudes of this kind rarely can be stated with such precision, but we will return to this point later. In the meantime let us proceed with the problem from the simplest standpoint.

If the mean value of ϵ $E(\epsilon_i) = 0$, it follows that $E(T_i) = E(t_i) = \tau_i$, thus the problem of determining an *unbiased* estimate of τ is identical with that of determining the form of the regression of the mean of T. The literature on the analytical theory of the regression of the mean is very large and has been well summarized in several places (cf., in particular, Kendall (1946), Ch .22). Here we will be content merely to give without proof a summary of the pertinent facts.

If we assume that τ can be represented with sufficient accuracy by a polynomial of order (p, q)

$$\tau(x, y) = \alpha_{00} + \alpha_{10}x + \alpha_{01}y + \cdots + \alpha_{pq}x^p x^q, \tag{1}$$

then formally at least (1) may be rewritten in the form

$$\tau(x, y) = \beta_{00} + \beta_{10}P_{10}(x, y) + \beta_{01}P_{01}(x, y) + \cdots + \beta_{pq}P_{pq}(x, y) \tag{2}$$

where the P's are polynomials (their orders indicated by their subscripts) which satisfy the following orthogonality condition:

$$\sum_i P_{rs}(x_i, y_i)P_{jk}(x_i, y_i) = 0, \qquad \text{if either } r \neq j \text{ or } s \neq k, \tag{3}$$

the summation extending over the occupied values of the independent variables x and y.

We may then write

$$t(x, y) = b_{00} + b_{10}P_{10}(x, y) + b_{01}P_{01}(x, y) + \cdots + b_{pq}P_{pq}(x, y) \qquad (4)$$

where b_{rs} is in each instance an unbiased estimate of β_{rs}.

In fitting the function (4) to the data we appeal, traditionally, to the principle of least squares, which states that the coefficients b_{rs} must be such as to make $\sum_i (\epsilon_i)^2$ a minimum. This principle admittedly is somewhat arbitrary in the strictest logical sense, but experience has shown it to be reliable; and in problems of regression of the mean there are good reasons to support its use. In the first place, the mean is an estimator that is unbiased and linear in the observations, and it is known that among such estimators the method of least squares selects those which have minimum variance. Also, if the residuals are normally distributed the method of least squares becomes equivalent to the method of maximum likelihood, which method leads to estimators that are *sufficient*—i.e., estimators that contain all of the information in the sample about the parameter or parameters under estimate. Normality of the residuals, however, is an hypothesis that is introduced only conditionally into a later stage of the work. If the residuals are not so distributed, justification for using the method of least squares becomes more or less empirical. For those who may wish to pursue this topic further, a recent review of the subject has been published by Durbin and Kendall (1951), who give not only a searching critique but also many extensions to the basic theorems.

Writing

$$t(x, y) = \sum_{r=0}^{p} \sum_{s=0}^{q} b_{rs}P_{rs}(x, y),$$

the equations to be solved are

$$\frac{\partial}{\partial b_{rs}} \sum_i \left\{ T_i - \sum_{r=0}^{p} \sum_{s=0}^{q} b_{rs}P_{rs}(x_i, y_i) \right\}^2 = 0.$$

Each of these equations is independent in all its parameters, and so from the orthogonality conditions,

$$\sum_i T_i P_{rs}(x_i, y_i) - b_{rs} \sum_i P_{rs}^2(x_i, y_i) = 0. \qquad (5)$$

Since each coefficient b_{rs} depends only upon P_{rs}, the series (4) may be either curtailed or extended (a procedure that might in certain cases be suggested by special tests of significance) without disturbing any of the lower-order terms. This is the special advantage of using orthogonal polynomials.

The coefficients b_{rs} may be computed from (5) once the polynomials P_{rs} have been specified. This will be done later for the general case of irregularly dis-

tributed data, but for the present we shall restrict ourselves to the special case in which the data are distributed at equal intervals in both x and y. Under these particular conditions it is possible to separate the two variables, so that $P_{rs}(x, y) = P_r(x)P_s(y)$. The polynomials then satisfy separate orthogonality conditions

$$\sum_{x=0}^{m} P_r(x)P_j(x) = 0, \; r \neq j \quad \text{and} \quad \sum_{y=0}^{n} P_s(y)P_k(y) = 0, \; s \neq k.$$

By taking the interval-values (which need not be the same) as the units of measure of the two variables and by making a suitable choice of origin, the independent variables may be replaced with the positive integers 0, 1, 2, $\cdots$, and the orthogonal polynomials then adopt a standard form which by convention is designated with the symbol ξ'. To avoid confusion, we shall use ξ_r' to designate the orthogonal polynomials in the x-variable, and η_s' to designate those in the y-variable, understanding of course that this is simply for visual convenience, and that values for η' are to be read from the tables of ξ'.

Tables of the ξ_r' polynomials at integral values of the argument have been published by DeLury (1950) up to $n = 26$, and for $0 \leqq r \leqq n$.

We may now rewrite (2) in the form

$$\tau(x, y) = \beta_{00}' + \beta_{10}'\xi_1'(x) + \beta_{01}'\eta_1'(y) + \cdots + \beta_{pq}'\xi_p'(x)\eta_q'(y) \qquad (6)$$

and for the estimate of τ based upon a regular $(m \times n)$ array of observations $(m > p, n > q)$,

$$t(x, y) = B_{00}' + B_{10}'\xi_1'(x) + B_{01}\eta_1'(y) + \cdots + B_{pq}'\xi_p'(x)\eta_q'(y) \qquad (7)$$

where B_{rs}' are unbiased estimates of B_{rs}'.

From (5)

$$B_{rs}' = g_{rs} \Big/ \sum_{j=0}^{m-1} \xi_r'^2(j) \sum_{k=0}^{n-1} \eta_s'^2(k). \qquad (8)$$

where

$$g_{rs} = \sum_{j=0}^{n-1} \sum_{k=0}^{n-1} T_{jk}\xi_r'(j)\eta_s'(k). \qquad (9)$$

The g_{rs} are obtained by direct calculation and the sums of squares of ξ_r' and η_s' are given at the foot of the tables of ξ'. The calculation of the array of g_{rs} may be programmed for automatic machines by writing down the total arrays of T, $\xi_r'(m)$ and $\eta_s'(n)$ (the two latter from the tables), and by instructing the machine to form the triple matrix product. These are the steps:

1. Write down the $(m \times n)$ array of data, $\boldsymbol{T}$
2. On the *right* of $\boldsymbol{T}$, write down the $(m \times m)$ array $\boldsymbol{\xi}'$.
3. Multiply $\boldsymbol{T} \times \boldsymbol{\xi}'$ as two matrices. The product will be an $(m \times n)$ array $\boldsymbol{h}$.

4. On the *left* of h, write down the transpose of the $(n \times n)$ array η'.

5. Multiply $\tilde{\eta}' \times h$ as two matrices. The product will be the $(m \times n)$ array g as required.

A hand-worked example is given by DeLury in a preface to the tables, and it is instructive to follow through these calculations step by step. Other examples have been given by Oldham and Sutherland (1955).

To determine the best values to use for p and q, we make use of the fact that the quantities

$$z_{rs} = g_{rs} \Big/ \left(\sum_{j=0}^{m-1} \xi_r'^2(j) \sum_{k=0}^{n-1} \eta_s'^2(k) \right)^{1/2}$$

are linearly related to the rth differences in the x-direction, and to the sth differences in the y-direction of the observations T_{jk} (DeLury, 1950). Consequently if the trend could be defined exactly by a polynomial of order (p, q) and if there were no residuals, $z_{rs}=0$ for $r>p$, $s>q$, and the choice of p and q would be obvious by looking at the array of z_{rs}. In practice, of course, trend is not confined to a finite polynomial and residuals are always present; therefore the best we can hope to do is to establish the practical limit for polynomial representation beyond which the addition of further terms does not significantly improve the fit. This limit will be adduced from a distinct break in the sequence of values of z_{rs} as one proceeds outward from the upper left-hand corner of the array.

There are advantages in using a table of z^2 rather than z for picking the trend. In the first place, it is more easily computed; and in the second, if the errors are normally distributed then z^2 is distributed like $\sigma^2\chi^2$ on 1 degree of freedom when trend has been removed. Consequently, by separating the z^2 array into two parts, viz.: that which is influenced by trend and that which is residual, any of the tests that are based upon the χ^2 distribution (such as F or Z) may be used for tests of significance. In discussing the merits of particular tests it is better to proceed by illustration, and so we shall resume this topic at a later stage.

The z^2 array may also be used to make a valuable check on the arithmetic up to this point, for

$$\sum_{j=0}^{m-1} \sum_{k=0}^{n-1} z_{jk}^2 = \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} T_{jk}^2.$$

When programming for automatic computation, this check should be included in the instructions.

The line that divides the z^2 array into its "trend" and "residual" parts we shall call, for convenience, the "trend limit."

When the separation of the z^2 array has been made, only those coefficients B_{rs}' which correspond with z_{rs}^2 values lying above and to the left of the trend limit are needed to specify the trend. The function t may then be calculated at

grid points from the tables of ξ' for contouring, or written as a function in x and y and calculated at specified locations.

If any of the coefficients B_{rs}' is in doubt, the following test may be helpful: if k coefficients are assigned to the trend and $\sum_{rs} z^2$ is the sum of the remaining z^2 terms, the quantity

$$t_{rs} = (B_{rs}' - \beta_{rs}')\left[\sum_{j=0}^{m-1} \xi_r'^2 \sum_{k=0}^{n-1} \eta_s'^2\right]^{1/2} \Big/ s, \quad s^2 = \sum_{rs} z^2/(mn - k - 1) \qquad (10)$$

should be distributed as "Student's" t with $\nu = mn - k - 1$ degrees of freedom, and this statistic may be used to test the hypothesis that $\beta_{rs}' = 0$. To test the significance of more than one coefficient, one may use Bartlett's (1934) test based upon the analysis of variance distribution, or combine t-tests into the composite χ^2 test (cf. Kendall, 1946, 21.51).

$$\chi^2 = -2 \sum^{\lambda} \log_e p_{rs},$$

on $\nu = 2\lambda$ degrees of freedom, where p_{rs} is the probability level of the value t_{rs}.

AN ILLUSTRATIVE PROBLEM

The following example is a gravity survey that was conducted over some known sulphide ore deposits at Val d'Or, Quebec, in 1947. This is not considered necessarily to be the most appropriate illustration, but it is the only published geophysical survey data known to the author. Moreover, the deposits have been extensively mined, and so the results can be compared with what is known to exist. The following is a brief account of the survey, (Innes, 1949):

Geologic setting

The property is situated on fairly level ground, with relief not exceeding 20 feet. The sulphide concentrations are covered with a swampy overburden varying between 10 and 50 feet in depth. They are encased in volcanic rocks of Keewatin age, which consists chiefly of a series of acidic to basic lavas, and which are highly altered in the vicinity of the disseminating sulphides. The ore consists chiefly of pyrite, chalcopyrite, pyrrhotite, sphalerite and a very small amount of galena, and carries some gold and silver. A major structural feature associated with the deposit (and bounding the orebody on the south-east and east) is an intrusive mass of coarse syenite porphyry.

Plan and precision of the survey

An area 1,700 feet square was laid out on a grid of carefully surveyed north south lines. On these lines, stations were spaced at 100-foot intervals (except near the orebodies where the spacing was shortened to 50 feet), and elevation differences were carried with a precision level with closure errors kept to one tenth

(*T* array)

DATA

| W ↑ | | |

of a foot. By repeated readings at thirteen field stations a probable error on a single observation of 0.4 gravity units was established. It was felt that most of this was reading error, and could be substantially reduced by using an instrument with a smaller scale value.[2] An elevation factor of 0.60 gravity units per foot was used.[3] Terrain corrections would not likely exceed 0.2 gravity units, and were therefore considered to be unnecessary.

Results

The main part of the Bouguer gravity map is shown in Figure 1, on a contour interval of one gravity unit. The picture is rather complex and there appears to be a good deal of near-surface effect. The surface geological information shown is not necessarily accurate, particularly in the eastern portion. At the time the map was made, very little exploratory work had been carried out between the 450 foot level and the surface. The position shown for the east orebody at the surface could possibly be as much as 150 feet in error. The 450 foot contours, however, are accurately shown. The data, with the base-station value as zero, are written as an array thus:

$$(T - \text{array})$$

$$\sum_{j=0}^{10} \sum_{k=0}^{16} T_{jk}^2 = 912{,}956.$$

The values enclosed in brackets correspond to stations that actually were missing, and these values have been estimated from the contours. We shall see how to deal with them presently.

Following the rules laid down in §1 these data lead to the z^2 array:

$$(z^2 \text{ array})$$

where

$$\sum_{j=0}^{10} \sum_{k=0}^{16} z_{jk}^2 = 912{,}948, \text{ giving a satisfactory check,}$$

and to the following first few coefficients

$$(\text{array of } B_{rs}').$$

The layout of data and coordinate axes has been chosen to make $m \leqq n$, for reasons that will appear in §4.

Adopting the principle that trend is revealed by terms that are "large," it is at once apparent that only a limited number of coefficients are required. Searching for the significant "break" in the sequence of values, we might make our first choice of trend limit the broken line, defining a function of degree 3 in x and of

[2] The scale value used was 0.2425 milligal per scale division.

[3] Although it was later found by sampling that the mean density of the country rock was 2.82 gms/cm³ giving an elevation factor of 0.58 gravity units per foot.

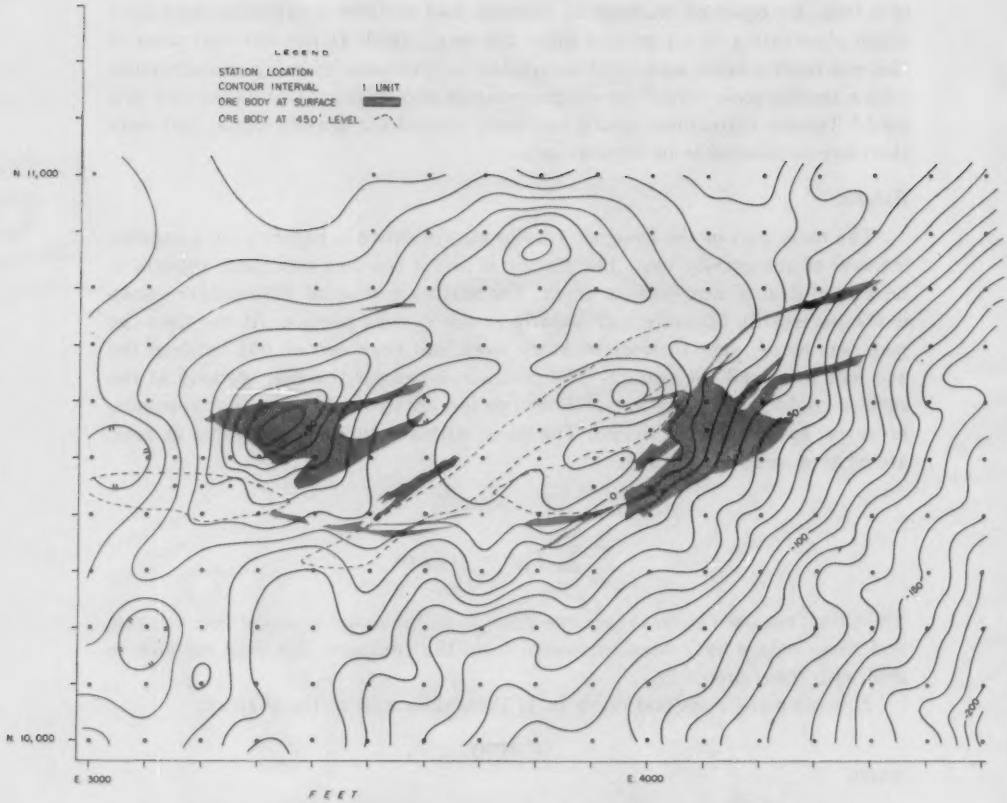

FIG. 1. Map of Bouguer gravity at East Sullivan, Val d'Or, Quebec (after Innes, 1949). Units: 10^{-2} milligal.

degree 4 in y. The outermost member of this group is $z_{32}^2 = 1532$, and the corresponding coefficient is (see table below) $B_{32}' = -0.006787$. In this instance $k = 13$ and $\sum_{res} z^2 = 19{,}044$; so that $s = (19{,}044/173)^{1/2} = 10.49$. Therefore on the hypothesis that $\beta_{32}' = 0$, we have from (10) and from the tables $n = 11$, $n = 17$ (Delury, 1950):

$$-t_{32} = 0.006787 \times (7752 \times 4290)^{1/2}/10.49$$
$$= 3.71 \text{ on } 173 \text{ degrees of freedom.}$$

Reference to the tables of t informs us that this value has a probability of occurrence of only 0.0001 if the hypothesis is true, therefore, we say that the estimate B_{32}' is "significantly different from zero," and accordingly we assign it to the

z^2 ARRAY

j \ k →										
309,300	97,110	17,690	2,189	1,700	30	371	1	0	13	54
288,260	54,847	4,197	414	517	404	86	5	256	0	13
100,354	2,323	12,822	1,532	9	101	96	115	0	0	56
1,520	654	368	144	271	32	387	0	33	8	0
13	130	105	56	231	688	22	61	158	5	5
1,245	0	492	0	190	168	26	12	53	108	48
20	9	235	123	433	865	9	42	1	106	21
618	221	126	25	395	129	289	146	220	8	25
90	77	280	2	0	42	731	29	371	10	20
30	13	48	102	181	3	61	383	19	120	117
82	133	17	271	34	0	72	8	24	26	171
10	268	109	33	85	9	0	22	2	200	237
90	0	7	107	21	2	3	51	119	14	1
20	26	12	70	0	9	2	19	25	156	26
1	5	87	71	136	14	8	12	74	14	4
2	15	23	16	14	49	77	28	6	18	7
21	37	0	237	104	14	205	51	1	41	9

ARRAY OF B_{rs}^{1}

r \ s	0	1	2	3	4	5	6	7
0	−40.6685	−7.2064	−1.1013	+0.1732	+0.5915	+0.09879	−0.04408	+0.003605
1	− 8.0143	−1.1055	+0.1095	−0.10538	−0.06655	+0.07969	−0.004335	+0.001644
2	− 1.0848	+0.05219	+0.04401	−0.006786	−0.001998	−0.009157	+0.001053	+0.001752
3	− 0.1888	+0.03915	−0.01053	−0.002940	+0.01563	−0.007315	−0.002985	−0.00008374
4	+ 0.008481	−0.008374	−0.002697	−0.0008787	−0.006940	+0.01621	+0.0003383	−0.0008645
5	+ 0.03351	−0.0001362	−0.002386	−0.0000128	+0.002566	−0.003271	−0.0001514	−0.0001585
6	+ 0.003156	+0.0006866	−0.001239	+0.0004006	+0.002913	−0.005575	+0.000068	+0.0002193
7	− 0.009844	−0.001860	+0.0005036	+0.0001006	−0.001543	+0.001195	+0.0002107	+0.0002278
8	+ 0.01231	−0.003509	−0.002397	+0.0000979	−0.0000002	+0.002189	−0.001071	+0.0003245
9	− 0.01304	+0.002723	−0.001899	+0.001233	+0.006357	−0.001338	−0.0005882	+0.002243

trend.[4] There is a temptation to allow tests of this type to assume the role of final arbiter in making decisions of this nature, but it should be remembered that they give statements only on probability and then only when the conditions under which they are valid are fulfilled. As we shall see in the next section, these conditions require careful checking before the results of such tests can be accepted at their face value.

TESTING THE RESIDUALS FOR HOMOGENEITY

There are two very good reasons for making a test of homogeneity on the "residual" z^2 elements after separating them from the trend: The first is to make sure that trend has adequately been removed, and the second is to guarantee the validity of significance tests that may be necessary when the trend-limit is difficult to pick. In precise gravity work, for example, the few extra z^2 terms which only upon analysis prove to be significant (even though at first they appear to be residual) may in a given instance make just the difference between a strong or a weak residual anomaly.

There is a very simple procedure for testing only the largest member of the residual z^2 array which is due to Cochran (1941). It consists in evaluating the probability of the statistic $v^2 = z_{max}^2 / \sum_{res} z^2$ on the hypothesis that z_{max}^2 was drawn from a homogeneous z^2 population, where the summation excludes z_{max}^2. This statistic has a known distribution when the z^2 quantities are each distributed independently like $\sigma^2\chi^2$, which follows, as DeLury has pointed out, when the ϵ's are normal. The distribution is rather complicated, but when the number of terms becomes large it assumes a simpler asymptotic form. If the total number of "residual" z^2 elements is R, and $R > 50$, a probability level for v^2 of 5 percent corresponds with a value given by the very simple asymptotic formula $v_{.05}^2 \sim 2(\gamma + \log_e R)/R$, where γ is Euler's constant, $=0.5772$. The largest term in the residual array is $z_{05}^2 = 1{,}245$ and the sum of the remaining terms is 17,799, thus $v^2 = 1{,}245/17{,}799 = 0.070$. For $R = 174$, $v_{.05}^2 = 2(.577 + 5.160)/174 = 0.066$, and we may therefore accept this as an indication that z_{05}^2 very probably does not belong in the residual portion of the array. This conclusion may readily be appreciated by plotting a frequency diagram for the z^2 values (Figure 2) and by superimposing upon it the theoretical frequency distribution of z^2/s^2 when ϵ is $N(0, \sigma)$ given by

$$f(z^2/s) = \frac{1}{2\sqrt{\pi\nu}} \cdot \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\Gamma\left(\frac{\nu}{2}\right)} \frac{s}{(z^2)^{1/2}(1 + z^2/\nu^2)^{(\nu+1)/2}}$$

where $\nu = R - 1 = 173$ degrees of freedom and $s^2 = 110$. The value 1,245 has an expected frequency of somewhat less than 1:4,000 which strongly suggests that

[4] Alternatively, we might reach the same conclusion by noting that the 95% (or 99%) "confidence interval" for β_{31}' does not contain the value zero.

this is altogether too rare an event to be accepted as a chance phenomenon. The trend limit, then, should be extended at least to include the coefficient B_{05}'.

This simple test is valuable for making a quick appraisal of a single z^2 value which appears on sight to be far out of line with its neighbours. It does not tell us anything about the homogeneity of the ensemble, for indeed homogeneity is a prior condition of validity for the test. If heterogeneity exists, the test tends to overestimate the probability values, which in turn overestimates the minimum significant value for z_{max}^2.

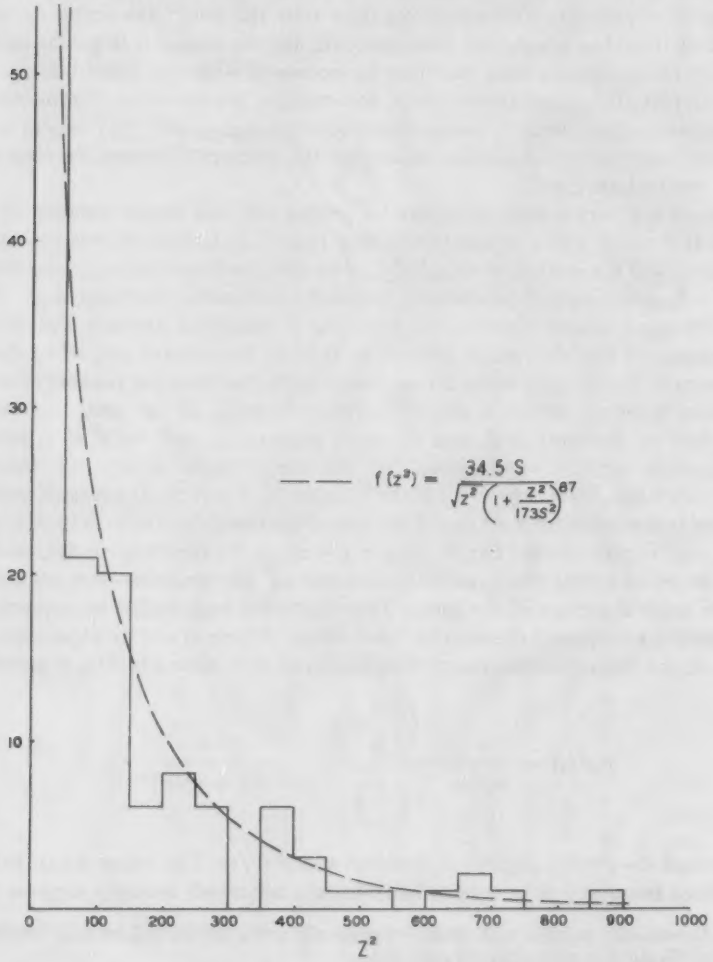

FIG. 2. Frequency diagram of elements in the s^2-array.

The direct test for homogeneity of the ensemble is the Neyman-Pearson likelihood-ratio test (1931). The likelihood statistic takes the form

$$L_1 = \prod_{res}^{R} (z^2)^{1/R}/s^2, \qquad s^2 = \sum_{res}^{R} z^2/R$$

when the degrees of freedom of all the samples are reduced to one. Obviously it has a maximum possible value of unity when all the z^2 values are equal. As is customary, we determine the theoretical sampling distribution of L_1 on the hypothesis that all of the residual z^2 values are estimates of a common variance, and then we use the actual value as a measure of the credibility of this hypothesis. The exact distribution function of this statistic has been deduced by Nair (1938), and 5 percent and 1 percent values have been tabulated for values of R up to 30 (Bishop & Nair, 1939). However, this function is very complicated and the writer has been unable to determine a limiting form for larger values of R. Neyman and Pearson have suggested, however, that when the samples have a small number of degrees of freedom the sampling distribution of L_1 might be approximated satisfactorily by a Pearson Type I formula:

$$p(L_1)dL_1 = [B(\mu, \nu)]^{-1} L_1^{\mu-1}(1 - L_1)^{\nu-1}dL_1 \qquad (11)$$

whose powers μ and ν are chosen such that the first two moments are those of L_1. It then turns out that for large values of $R(\geqq 100$, say) the probability is 0.05 that L_1 will fall below a value $(L_1)_{.05}$ which is given by

$$(L_1)_{.05} = [1 + 2{\cdot}557Ae^B]^{-1} \qquad (12)$$

where

$$A = 1 - \frac{3.88}{R - 12} \quad \text{and} \quad B = \frac{4.329}{R - 14} + \frac{2.376}{R - 9},$$

if the ensemble is homogeneous. The derivation of (12) is given as an appendix to this paper. For $R=174$, $(L_1)_{.05}=0.215$. The observed value of L_1 (replacing all z^2 values listed as zero with the value 1) is 0.286. Actually, this value corresponds with an expectation of 0.5, and therefore this test casts no doubt upon the homogeneity of the ensemble.

The power of the L_1 test, however, is very low when the degrees of freedom within the samples are as small as unity (cf. Brown, 1939). Therefore we should expect it to detect only very large departures from homogeneity, and in many instances this may be insufficient for our needs. Thus we are forced to consider alternatives to the L_1 test in which we increase the number of degrees of freedom in the samples by grouping. The most natural way in which to group the z^2 terms is along the parallels of the second diagonal of the array, since these groups correspond with sets of terms which are homogeneous in x and y. Then we may use a test due to Hartley (1940), which employs a statistic related to L_1:

$$M = R \log_e \left[\sum_{t=1}^{k} (n_t s_t^2)/R \right] - \sum_{t=1}^{k} (n_t \log_e s_t^2)$$

where s_t^2 is the mean of the tth sample of z^2 values containing n_t observations, so that $\sum_{t=1}^{k} n_t = R$. The layout for computing M is shown in Table I, and the value turns out to be 48.22. Reference to the tables of the "percentage points" of the sampling distribution of M (Thompson and Merrington, 1943) shows that this value has a probability of occurrence of less than 0.01 if the samples have been drawn from a homogeneous population, and therefore we conclude that they have not. Thus, according to this grouping scheme at least, the residual ensemble now appears to be markedly inhomogeneous. This conclusion is made clear by Figure 3, which shows the ordering among the s_t^2 values.

TESTING RESIDUALS FOR SERIAL CORRELATION

Heterogeneity among samples grouped as above might well have been expected. After all, we are trying to represent a complicated function with a finite polynomial, and there is no reason to suppose that the cut-off necessarily should be sharp. The ordering revealed among the "residual" z^2 terms is clear evidence of the persistence of the effects of trend through that part of the array, and not until we reach terms of the seventeenth power does it appear to die away. Now one obviously cannot use a polynomial of such a high order for a definition of trend; for not only would such a function be very unwieldy, but it would tend to

TABLE I

t	n_t	$n_t S_t^2$	S_t^2	$\log_e S_t^2$	$n_t \log_e S_t^2$
1	3	1,081	360.33	5.89	17.65
2	5	2,290	458.00	6.12	30.61
3	7	1,053	150.43	5.01	35.07
4	8	1,634	204.35	5.32	42.56
5	9	910	101.11	4.61	41.49
6	10	2,005	200.52	5.30	53.00
7	11	1,077	97.91	4.58	50.38
8	11	1,586	144.18	4.97	54.67
9	11	849	77.18	4.35	45.85
10	11	1,012	92.00	4.52	49.72
11	11	1,095	99.55	4.60	50.60
12	11	675	61.36	4.12	45.32
13	11	1,078	98.00	4.58	50.38
14	10	195	19.50	2.97	29.70
15	9	350	38.89	3.61	32.49
16	8	463	57.88	4.06	32.48
17	7	670	95.71	4.56	31.92
18	6	379	63.17	4.15	24.90
19	5	464	92.80	4.53	22.65
20	4	97	24.25	3.19	12.76
21	3	24	8.00	2.08	6.24
22	2	48	24.00	3.18	6.36
	$N=174$	19,044			768.80

$N \log_e [\sum(n_t S_t^2)/N] = 817.02$, $M = 48.22$.

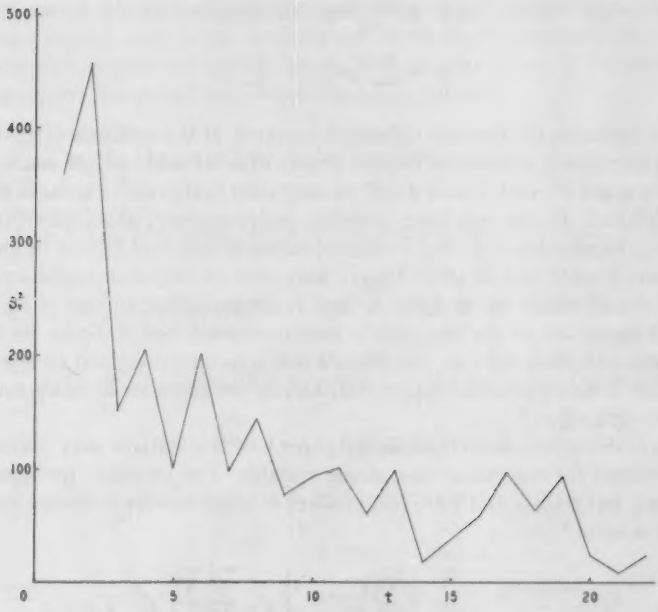

FIG. 3. Ranking diagram of grouped sample variances s_t^2.

defeat the aim of smoothing the data. So the question is, where are we entitled to cut it off?

To answer this question, we must formulate more precisely what we mean by "trend." As most of us rather vaguely understand it, trend is that part of the data that varies smoothly. By "smoothly," we mean that over reasonably short intervals trend can be interpolated or extrapolated with confidence. In other words, it is a function which behaves predictably, or in engineering parlance, it is fully "autocorrelated." Now if this is what we mean by trend, then the residuals, if they are to be trend-free, must contain no predictable elements—at least, not to any significant degree. Consequently, as a practical definition of trend, we are led to choose "the simplest function whose residuals are trend-free." This begs the question of defining trend itself, but it is an approach at least which leads directly to results.

For a one-dimensional array of data, a suitable criterion for testing for serial correlation (or "autocorrelation") among the residuals ϵ_i might be the null hypothesis in the simple Markov chain

$$\epsilon_i = \rho\epsilon_{i-1} + u_i \qquad |\rho| < 1.$$

where u_i is a random variable which is normally distributed with zero mean, and which is independent both of $\epsilon_{i-1}, \epsilon_{i-2}, \cdots$, and of $u_{i-1}, u_{i-2}, \cdots$. The null hypothesis is the hypothesis that $\rho = 0$.

Durbin and Watson (1950) have proposed using for this test the statistic

$$d = \sum_i (\Delta\epsilon_i)^2 \Big/ \sum_i \epsilon_i^2$$

where Δ indicates the forward difference operator. If the residuals are positively serially correlated, d tends to become small; thus we wish to find some critical value for d, say d^*, such that if $d<d^*$ we may infer that positive serial correlation is established. It has not been possible, unfortunately, to obtain the exact sampling distribution of d, and so critical values of this kind cannot be obtained. However, Durbin and Watson (1951) were able to calculate upper and lower bounds for d^* which we may call d_U and d_L, respectively; so that if $d \leqq d_L$, the value is significant at the probability level concerned, and if $d \geqq d_U$, its value is not significant. If $d_L<d<d_U$, the bounds test is inconclusive, and an alternative procedure is recommended. Tables of d_L and d_U are given for $P=0.05$, 0.025 and 0.01, for $15 \leqq n \leqq 40$.[5]

The authors describe in their second paper how this statistic may conveniently be calculated for regression on a single variable. The bivariate problem is not discussed, but since x and y are independent we shall use the following extension of their scheme.[6] Let

$$d_y = \sum_{j=0}^{m-1}\left\{\sum_{k=0}^{n-1}(\Delta_y\epsilon_{jk})^2\right\} \Big/ \sum_{j=0}^{m-1}\sum_{k=0}^{n-1}\epsilon_{jk}^2$$

where Δ_y symbolizes the forward difference operator in the direction of y, so that $\Delta_y\epsilon_{jk}=\epsilon_{jk+1}-\epsilon_{jk}$. By convention, the system of coördinates shall always be such that $n \geqq m$. It is easily shown that the denominator $=\sum_{rs} z^2$, and if $t(x, y)$ is a polynomial of order (p, q), then it follows from the identity

$$\sum_{k=0}^{n-1}\Delta\eta_a'(k)\Delta\eta_b'(k) = -2\eta_b'(0)\Delta\eta_a'(-1), \qquad a+b \text{ even},\ a \leqq b,$$

$$= 0, \qquad a+b \text{ odd},$$

that

$$\sum_{j=0}^{m-1}\sum_{k=0}^{n-1}(\Delta_y\epsilon_{jk})^2 = \sum_{j=0}^{m-1}\sum_{k=0}^{n-1}(\Delta_y T_{jk})^2 - 2\sum_{r=0}^{p}\sum_{s=0}^{q}B_{rs}'\sum_{j=0}^{m-1}\xi_r'\sum_{k=0}^{n-1}(\Delta_y T_{jk}\cdot\Delta\eta_s')$$

$$- 2\sum_{r=0}^{p}\left(\sum_{j=0}^{m-1}\xi_r'^2\right)\sum_{s=1}^{q}\sum_{b=1}^{q}B_{rs}'B_{rb}'\eta_b'(0)\,\Delta\eta_a(-1) \qquad (13)$$

[5] The distribution function of d_L and d_U is an infinite series of incomplete Beta-functions, whose coefficients are the Jacobi polynomials orthogonalized in (0, 1) with respect to the distribution (11).

[6] The author has not been able to put this extension of the one-dimensional model on a sufficiently rigorous theoretical basis to outline a proof here. This section does not in any event constitute an essential part of the paper, in the author's consideration.

for $a+b$ even, $a \leqq b$. It is understood that the summations in the second and third terms include only those coefficients B_{rs}' which are considered significant. The labor that is involved in computing this quantity is not so formidable as may appear, for the second term breaks down as follows[7]

$$s = 1 \quad \sum_{j=0}^{m-1} \xi_r'(j) \sum_{k=0}^{n-1} (\Delta_y T_{jk} \Delta\eta_1'(k)) = \Delta\eta_1'(-1)(h_{rn-1} - h_{r0})$$

$$s = 2 \quad \sum_{j=0}^{m-1} \xi_r'(j) \sum_{k=0}^{n-1} (\Delta_y T_{jk} \Delta\eta_2'(k)) = -2\lambda_2(n) g_{r0} - \Delta\eta_2'(-1)(h_{rn-1} + h_{r0})$$

$$s = 3 \quad \sum_{j=0}^{m-1} \xi_r'(j) \sum_{k=0}^{n-1} (\Delta_y T_{jk} \Delta\eta_3'(k)) = -6 \frac{\lambda_3(n)}{\lambda_1(n)} g_{r1} + \Delta\eta_3'(-1)(h_{rn-1} - h_{r0})$$

$$s = 4 \quad \sum_{j=0}^{m-1} \xi_r'(j) \sum_{k=0}^{n-1} (\Delta_y T_{jk} \Delta\eta_4'(k)) = -12 \frac{\lambda_4(n)}{\lambda_2(n)} g_{r2} - \frac{4\lambda_4(n)}{7} (n^2 + 5) g_{r0} - \Delta\eta_4'(-1)(h_{rn-1} + h_{r0})$$

$$s = 5 \quad \sum_{j=0}^{m-1} \xi_r'(j) \sum_{k=0}^{n-1} (\Delta_y T_{jk} \Delta\eta_5'(k)) = -20 \frac{\lambda_5(n)}{\lambda_3(n)} g_{r3} = \frac{4\lambda_5(n)}{\lambda_1(n)} (n^2 + 11) g_{r1} + \Delta\eta_5'(-1)(h_{rn-1} - h_{r0}).$$

$$s = 6 \quad \sum_{j=0}^{m-1} \xi_r'(j) \sum_{k=0}^{n-1} (\Delta_y T_{jk} \Delta\eta_6'(k)) = -30 \frac{\lambda_6(n)}{\lambda_4(n)} g_{r4} - \frac{180\lambda_6(n)}{77\lambda_2(n)} (n^2 + 19) g_{r2} - \frac{\lambda_6(n)}{11} (n^4 + 35n^2 + 84) g_{r0} - \Delta\eta_6'(-1)(h_{r(n-1)} + h_{r0})$$

where

$$h_{rk} = \sum_{j=0}^{m-1} T_{jk} \xi_r'(j).$$

All of the quantities g_{rs} and h_{rk} will be available from earlier computations (§1), and the quantities $\lambda_s(n)$ are given by (DeLury, 1950)

$$\lambda_s(n) = \frac{\eta_s'(n-1) \cdot (2s)!}{(s!)^2 (n-1)(n-2) \cdots (n-s)}.$$

The values of $\Delta\eta_s'(-1)$ are obtained by writing down the first few terms of $\eta_s'(k)$ from the tables and preparing a small array of differences. Table II illustrates the layout for $n = 17$. The values required are printed in italics.

[7] These are analogous to formulae given by Durbin and Watson (1951). However, their formulae for $\sum \Delta y \Delta \xi_4'$ and for $\sum \Delta y \Delta \xi_5'$ are incorrect.

TABLE II

$\eta = 17$

y	η_1'	$\Delta\eta_1'$	η_2'	$\Delta\eta_2'$	$\Delta^2\eta_2'$	η_3'	$\Delta\eta_3'$	$\Delta^2\eta_3'$	$\Delta^3\eta_3'$	η_4'	$\Delta\eta_4'$	$\Delta^2\eta_4'$	$\Delta^3\eta_4'$	$\Delta^4\eta_4'$	η_5'	$\Delta\eta_5'$	$\Delta^2\eta_5'$	$\Delta^3\eta_5'$	$\Delta^4\eta_5'$	$\Delta^5\eta_5'$
0	−8	+1	+40	−17		−28	+29			+52	−119				−104	−523				
1	−7	+1	+25	−15	+2	−7	+21	−8	+1	−13	−65	+54	−17		+91	+195	−328	+195		
2	−6	+1	+12	−13	+2	+7	+14	−7	+1	−39	−26	+39	−15		+104	+13	−182	+146	−48	
3	−5	+1	+1	−11	+2	+15	+8	−6	+1	−39	0	+26	−13	+2	+39	−65	−78	+104	−42	+6
4			−8	−9	+2	+18	+3	−5	+1	−24	+15	+15	−11	+2	−36	−75	−10	+68	−36	+6
5						+17	−1	−4	+1	−3	+21	+6	−9	+2	−83	−47	+28	+38	−30	+6
6										+17	+20	−1	−7	+2	−88	−5	+42	+14	−24	+6

Taking the broken line in the z^2 array as the first estimate of the trend limit, the computation of

$$\sum_{j=0}^{m-1} \sum_{k=0}^{n-1} (\Delta_y \epsilon_{jk})^2$$

is illustrated in Table III.

$$\sum_j \sum_k (\Delta_y T_{jk})^2$$

is calculated directly, and its value is 58,121.

$$\sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}' \sum_j \xi_r' \sum_k \Delta_y T_{jk} \Delta \eta_s' = + 34{,}630$$

$$\sum_{r=0}^{p} \left(\sum_{j=0}^{m-1} \xi_r'^2 \right) \sum_{a=1}^{q} \sum_{b=1}^{q} B_{ra}' B_{rb}' \eta_b'(0) \Delta \eta_a'(-1) = - 18{,}331$$

Thus

$$\sum_j \sum_k (\Delta_y \epsilon_{jk})^2 = 58{,}121 - 69{,}260 + 36{,}662 = 25{,}523$$

And since

$$\sum_j \sum_k \epsilon_{jk}^2 = \sum_{rs} s^2 = 19{,}044 \text{ as before,}$$

$$d_y = 25{,}523/19{,}044 = 1.34.$$

Reference to the tables prepared by Durbin and Watson shows that for a polynomial of order 3 this value is inconclusive both at probability levels of 0.05 and 0.01, but that it leans more strongly toward d_L at the former level and toward d_U at the latter. Unfortunately, when n is as small as 17 the bounds test becomes very diffuse, and one must expect to obtain only very rough indications of this kind.

When the bounds test cannot be applied, or, as in the present case, when it leads to inconclusive results, an approximate test may be used which was devised also by Durbin & Watson (1951). The test consists in fitting the sampling distribution of $\frac{1}{4}d_y$ to a function of the type (11) by matching the first two moments,and then using the percentage points of the resulting distribution to test the significance of the observed d_y.

Thus if d_y is distributed as

$$p(d_y) = [B(\mu, \nu)]^{-1} \cdot (\tfrac{1}{4}d_y)^{\mu-1} \cdot (1 - \tfrac{1}{4}d_y)^{\nu-1}$$

then

$$E(d_y) = \frac{4\mu}{\mu + \nu}, \qquad \text{var}\,(d_y) = \frac{16\mu\nu}{(\mu + \nu)^2(\mu + \nu + 1)}.$$

TABLE III

$$-\tfrac{1}{2}T_2=\sum_{r=0}^{p}\sum_{s=0}^{q}B_{rs}'K_{rs}' \qquad K_{rs}'=\sum_{i=0}^{m-1}\xi_i'\sum_{k=0}^{n-1}\Delta_s T_{ik}\Delta\eta_s'.$$

n = 17:

$$\begin{aligned}K_{r1}'&=h_{r16}-h_{r0}\\K_{r2}'&=-2g_{r0}+17(h_{r16}+h_{r0})\\K_{r3}'&=-g_{r1}+29(h_{r16}-h_{r0})\\K_{r4}'&=-g_{r2}-14g_{r0}+119(h_{r16}+h_{r0})\\K_{r5}'&=-6g_{r3}+20g_{r1}+523(h_{r16}-h_{r0})\end{aligned}$$

where

$$h_{rk}=\sum_{j=0}^{m-1}T_{jk}\xi_r'.$$

r	$h_{r16}-h_{r0}$	$h_{r16}+h_{r0}$	K_{r1}'	K_{r2}'	K_{r3}'	K_{r4}'	K_{r5}'
0	−1,481	−1,827	−1,481	−15,849	−6,981	−18,440	−6,903
1	−1,762	−1,218	−1,762	+ 6,246	−1,483		
2	+ 648	+ 572	+ 684	+41,852			
3	−1,592	− 938	−1,592	− 9,138			
				$-\tfrac{1}{2}T_2=+34,630$			

$$-\tfrac{1}{2}T_3=\sum_{r=0}^{p}\Big(\sum_{j=0}^{m-1}\xi_r'^2\Big)\sum_{a=1}^{q}\sum_{b=1}^{q}B_{ra}'B_{rb}'\eta_b'(1)\Delta\eta_a'(0),\ a\leqq b,\ a+b \text{ even}.$$

Table of $B_{ra}'B_{rb}'$

$\sum_{j=0}^{m-1}\xi_r'^2$	r	$a=1$ $b=1$	$a=1$ $b=3$	$a=2$ $b=2$	$a=3$ $b=3$	$\sum_{a=1}^{3}\sum_{b=1}^{3}B_{ra}'B_{rb}'\eta_b'(1)\Delta\eta_a'(0)$	$\sum_{j=0}^{m-1}\xi_r'^2\sum_{a=1}^{3}\sum_{b=1}^{3}B_{ra}'B_{rb}'\eta_b'(1)\Delta\eta_a'(0)$
11	0	+64.2990	+1.5131	+1.17679	+0.03565	−1,427.73	−15,705
110	1	+ 1.2221	−0.04328	+0.002724	+0.001533	− 11.6291	− 1,279
858	2	+0.01199	*	+0.001937	*	− 1.41308	− 1,212
4,290	3	*	*	+0.000046	*	− 0.03132	− 135
	$\eta_b'(1)\Delta\eta_a'(0)$	−8	−28	−680	−812		$\tfrac{1}{2}T_3=-18,331$

so that

$$\mu + \nu = \frac{E(d_y)[4 - E(d_y)]}{\text{var}\,(d_y)} - 1$$

and

$$\mu = \tfrac{1}{2}(\mu + \nu)E(d_y).$$

where

$$E(d_y) \cong \frac{2(n-1)}{n-q-1}$$

$$\text{var}\,(d_y) \cong \frac{4(3n-4)}{(n-q-1)(n-q+1)} - \frac{8(n-1)^2}{(n-q-1)^2(n-q+1)}.$$

Thus for $n=17$, $q=3$

$$E(d_y) = 2.41, \qquad \text{var}\,(d_y) = 0.18,$$
$$\mu = 11.9, \qquad \nu = 7.8$$

Taking 2μ, 2ν to the nearest integers, we find from the tables of the Incomplete Beta-function (Thompson, 1941) that $(\frac{1}{4}d_y)_{.05}=0.4247$ and $(\frac{1}{4}d_y)_{.01}=0.3507$, or $(d_y)_{.05}=1.58$ and $(d_y)_{.01}=1.32$. On the basis of both tests, therefore, a slight amount of positive serial correlation is suggested, although for $n=17$ these tests admittedly are very rough.

We have already seen (§3) that the term z_{05}^2 is too large to belong to the residual z^2 ensemble. Another large term although not so prominent is z_{13}^2. We now extend the position of the trend limit out to the solid line in order to take these extra terms into the trend. This reduces the statistic M to the value 44.20 which, however, is still significant at the 1 percent probability level; but it raises the value of d_y to 1.52, which can no longer be said to be significant at 5 percent. Having thus made the residuals essentially trend-free, we accept the modified partition as final.

The procedure thus far may be summed up as follows:

1. Partition the z^2 array by inspection. Use the major "break."
2. Group the "residual" terms parallel to the second diagonal of the array and calculate M.
3. If the value is significant, calculate d_y.
4. If the value is significant, take into the "trend" the largest term(s) lying adjacent to the boundary and adjust the value of M.
5. If the value is still significant, make the correction to d_y.
6. If the value is still significant, take in the next largest terms, and so on.

PROCEDURE WHEN SOME OF THE DATA ARE MISSING

Suppose now that one or several values are missing from the plot of the data. Such may be the case, for example, where a variable density of coverage is imposed by terrain or by roads, and some of the grid points may fall more than half a spacing unit from the nearest points of control. When this occurs, the procedure is first to guess at the missing values, and then systematically to reduce the weights of these values in determining the coefficients of $t(x, y)$ from unity to zero. The process is a simple extension of the so-called "missing plot techniques" due to Hartley (1951).

In a regular $(m \times n)$ array of $N = mn$ points at which observations have been made, suppose that values are available at N_ψ points and missing at N_θ points. Then $N_\psi + N_\theta = N$. We rewrite (7) in the abridged form

$$t(x, y) = \sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}' \xi_r'(x) \eta_s'(y)$$

understanding, of course, that the summation extends only over those coefficients that are judged to be significant. We then proceed to fit this function to the subset N_ψ by choosing the coefficients B_{rs}' so that

$$\sum^{N\psi} \left\{ T_\psi - \sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}' \xi_r'(x_\psi) \eta_s'(y_\psi) \right\}^2 = \text{a minimum.}$$

To do so, we make estimates of the N_θ missing observations, which we call U_θ. Then we minimize the function

$$Q(B_{rs}', U_\theta) = \sum^{N\psi} \left\{ T_\psi - \sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}' \xi_s'(x_\psi) \eta_s'(y_\psi) \right\}^2 + \sum^{N\theta} \left\{ U_\theta - \sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}' \xi_r'(x_\theta) \eta_s'(y_\theta) \right\}^2$$

with respect to the set of variables B_{rs}' and U_θ. This leads to the simultaneous equations

$$B_{rs}'(U_\theta) = \left[\sum^{N\psi} T_\psi \xi_r'(x_\psi) \eta_s'(y_\psi) + \sum^{N\theta} U_\theta (B_{rs}') \xi_r'(x_\theta) \eta_s'(y_\theta) \right] \Big/ \sum_{j=0}^{m-1} \xi_r'^2 \sum_{k=0}^{n-1} \eta_s'^2$$

and

$$U_\theta(B_{rs}') = \sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}'(U_\theta) \xi_r'(x_\theta) \eta_s'(y_\theta)$$

which may be solved approximately by iteration.

These are the steps:

1. Make estimates U_θ of the missing observations, either from contours or from profiles.

2. Using these values, compute the z^2 array and select the set of significant coefficients. Let the first values so obtained be b_{rs}'.

3. Calculate the values

$$u_\theta = \sum_{r=0}^{p} \sum_{s=0}^{q} b_{rs}' \xi_r'(x_\theta) \eta_s'(y_\theta)$$

at the missing points. Let the first differences $U_\theta - u_\theta = \Delta u_\theta$.

4. If these are not negligible, compute first corrections to b_{rs}' as follows:

$$\Delta b_{rs}' = \frac{\partial}{\partial u_\theta} B_{rs}'(u_\theta) \Delta u_\theta.$$

$$= \sum^{N\theta} \Delta u_\theta \xi_r'(x_\theta) \eta_s'(y_\theta) \Big/ \sum_{j=0}^{m-1} \xi_r'^2 \sum_{k=0}^{n-1} \eta_s'^2.$$

5. Compute second corrections to U_θ as follows:

$$\Delta^2 u_\theta = \frac{\partial}{\partial B_{rs}'} U_\theta(B_{rs}') \Delta b_{rs}' = \sum_{r=0}^{p} \sum_{s=0}^{q} \Delta b_{rs}' \xi_r'(x_\theta) \eta_s'(y_\theta).$$

6. If these are not negligible, compute second corrections to b_{rs}' as follows:

$$\Delta^2 b_{rs}' = \sum^{N\theta} \Delta^2 u_\theta \xi_r'(x_\theta) \eta_s'(y_\theta) \Big/ \sum_{j=0}^{m-1} \xi_r'^2 \sum_{k=0}^{n-1} \eta_s'^2$$

and so on, until the differences at U_θ lose significance.

7. Finally,

$$B_{rs}' = b_{rs}' + \Delta b_{rs}' + \Delta^2 b_{rs}' + \cdots$$

and

$$\epsilon_\theta = \Delta u_\theta - \Delta^2 u_\theta - \cdots$$

Generally speaking, this process converges quite rapidly.

Test of significance: For most applications, the following simple test should be adequate: If k is the number of terms assigned to the trend, and if

$$s'^2 = \left(\sum_{res} z^2 - \sum^{N\theta} \epsilon_\theta^2 \right) \Big/ (N_\phi - k - 1),$$

where

$$\epsilon_\theta = U_\theta - \sum_{r=0}^{p} \sum_{s=0}^{q} B_{rs}' \xi_r'(x_\theta) \eta_s'(y_\theta),$$

then the quantity

$$l_\theta = \epsilon_\theta / s'$$

should be distributed approximately as t on $N_\psi - k - 1$ degrees of freedom. Those differences which give a value of t having a probability of less than 0.5 may be said to have exceeded the "probable error" of the observations, and may therefore be considered unlikely. If N_ψ is moderately large, the p.e. $= 0.67s'$.

Now consider the missing points in the survey. Estimates of the Bouguer gravity at these locations previously have been made by extrapolating the contours, and the values are enclosed in brackets in the matrix presentation of the data (§2). First differences are given below.

						$\rightarrow E$
	*	0	1	3	−1	1
↓	1	−5	−8	−10	−10	
S	*	*	−5	−8	*	
	*	*	−1	*	*	

Here $s' = (16{,}740/157)^{1/2} = 10.33$, so that the p.e. on 157 degrees of freedom $= 7$, or 0.7 gravity units. The first differences that exceed this figure are underscored; the remainder may be neglected. These give first corrections to the coefficients as follows:

$r/s \rightarrow$				
↓ −0.2781	+0.1069	−0.0176	−0.0060	+0.0641
+0.0557	−0.0214	+0.0035		
+0.0002	−0.00011	+0.00003	0.0000	
−0.0181	+0.00694			
+0.00952				
−0.00106				

which in turn lead to the following set of cumulative second differences:

$\rightarrow E$					
*	−1	−3	+5	+1	+1
↓ +2	−3	−5	−7	−7	
S		−3	−4		
		0			

Since none of these values is significant, the calculations may be stopped at this point. The final set of coefficients is, therefore:

$r/s \rightarrow$				
↓ −40.04	−7.0995	−1.1189	+0.1672	+0.6556
− 7.9586	−1.2369	+0.1130		
− 1.0846	+0.05208	+0.04404	−0.006787	
− 0.2069	+0.04609			
+ 0.01800				
+ 0.03245				

These coefficients specify the unbiased estimate $t(x, y)$ of r. The map of this function is shown in Figure 4, and the map of the residuals in Figure 5. These results will not be discussed in this paper. However, for a comparison with the results obtained by a skilled analyst using visual smoothing, the reader is referred to the paper by Innes.

RANDOMLY DISTRIBUTED DATA

Of course, it seldom happens in practice that data are acquired at an evenly spaced set of points, and to apply the DeLury method it would in general be

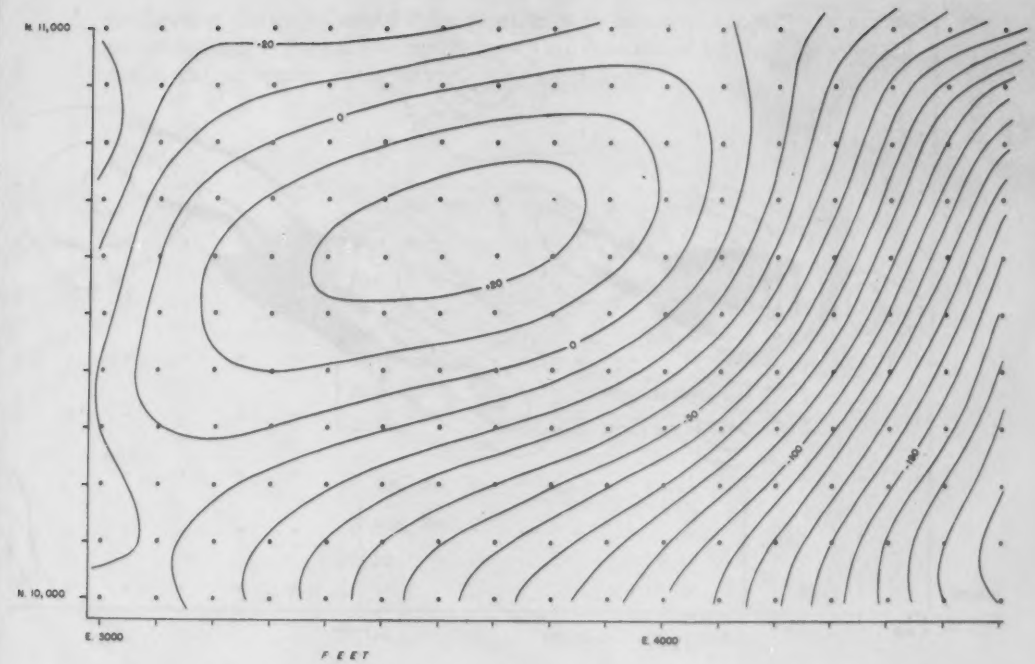

FIG. 4. Map of the unbiased trend-estimate $t(x, y)$. Units: 10^{-2} milligal.

necessary to make a regular sampling. Most of the sample values would be estimated from contours, and the grid so arranged that the sampling points (except for those regarded as "missing") would lie close to points of control, so that the interpolations could be performed with some confidence. Nevertheless, sampling geophysical data by estimating from contours is a somewhat contentious procedure, and there are many who, understandingly enough, object to it. The main point at issue seems to be that the sampling process does not take into account the actual distribution of the control, but replaces it with a purely hypothetical one that is perfectly uniform. Thus although some of the sample values are naturally weaker than others, all are given equal weight in estimating the trend. If the pattern of control is highly irregular, it might be more realistic to accept it as it is, and to allow the weighting distribution to vary accordingly. Moreover, the sampling process always greatly reduces the number of points that is used, and there may be some risk of losing useful information thereby.

These objections can scarcely be argued, and for those who subscribe to this view, the alternative procedure is as follows: Given a set of data T_i measured at N points $(x, y)_i$, $i = 1, 2, 3, \cdots, N$. Then we assume that τ is representable by a series of polynomials up to order (p, q) as before:

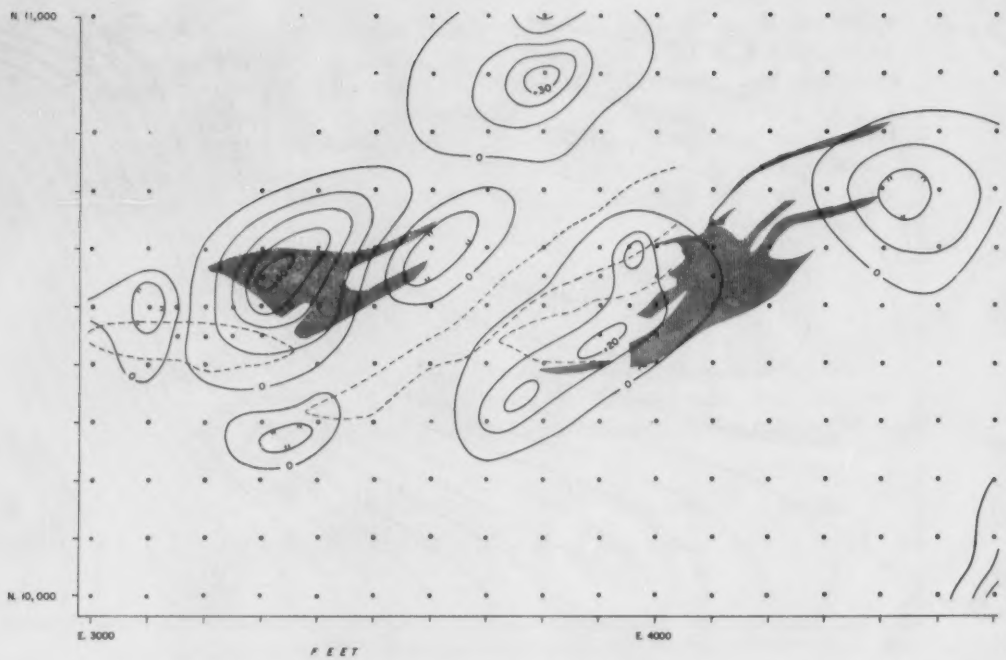

FIG. 5. Map of the residuals obtained by subtracting $t(x, y)$ from the Bouguer gravity. Units: 10^{-2} milligal.

$$\tau(x, y) = \beta_{00} + \beta_{10}P_{10}(x, y) + \beta_{01}P_{01}(x, y), + \cdots + \beta_{pq}P_{pq}(x, y)$$

Unfortunately, when the points are irregularly spaced we cannot make a separation of the variables x and y, and so we must make estimates of the coefficients β_{rs} from the relations (5):

$$b_{rs} = \sum_{i}^{N} T_i P_{rs}(x_i, y_i) \Big/ \sum_{i}^{N} P_{rs}^2(x_i, y_i)$$

where $P_{rs}(x, y)$ are polynomials in x and y which satisfy the orthogonality conditions (3).

If we write

$$P_{rs}(x, y) = \sum_{\alpha=0}^{r} \sum_{\beta=0}^{s} c_{\alpha\beta}^{rs} x^\alpha y^\beta$$

it becomes clear that P_{rs} contains $(r+1)(s+1)$ coefficients, but that the orthogonality relations (3) impose only $(r+1)(s+1)-1$ conditions upon them, so that one coefficient in each polynomial is assignable at will. There is some advantage

in choosing the coefficient of the highest term to be unity, i.e., $c_{rs}{}^{rs} = 1$; and in particular, $c_{00}{}^{00} = P_{00} = 1$. The remaining c's are determined by the relations (3), and it may be verified that

$$c_{\alpha\beta}{}^{rs} = \Delta_{\alpha\beta}{}^{(rs)}/\Delta^{(rs-1)}$$

where

$$\Delta^{(rs)} = \begin{vmatrix} \mu_{00} & \mu_{10} & \mu_{01} & \cdots & \mu_{r,s-1} & \mu_{r-1,s} & \mu_{rs} \\ \mu_{10} & \mu_{20} & & & & & \cdot \\ \mu_{01} & & & & & & \cdot \\ \cdot & & & & & & \cdot \\ \cdot & & & & & & \cdot \\ \mu_{r,s-1} & & & & & & \mu_{2r,2s-1} \\ \mu_{r-1,s} & & & & & \mu_{2r-s,2s} & \mu_{2r-1,2s} \\ \mu_{rs} & & & \cdots & \mu_{2r,2s-1} & \mu_{2r-1,2s} & \mu_{2r,2s} \end{vmatrix}$$

and

$$\Delta^{(rs-1)} = \begin{vmatrix} \mu_{00} & \mu_{10} & \mu_{01} & \cdots & \mu_{r,s-1} & \mu_{r-1,s} \\ \mu_{10} & \mu_{20} & & & & \cdot \\ \mu_{01} & & & & & \cdot \\ \cdot & & & & & \cdot \\ \cdot & & & & & \cdot \\ \mu_{r,s-1} & & & & \mu_{2r,2s-2} & \mu_{2r-1,2s-1} \\ \mu_{r-1,s} & & & \cdots & \mu_{2r-1,2s-1} & \mu_{2r-2,2s} \end{vmatrix}$$

$$\mu_{ab} = \sum_{i=1}^{N} (x_i{}^a y_i{}^b)$$

Here $\Delta_{\alpha\beta}^{(rs)}$ indicates the minor of the term $\mu_{\alpha+r,\beta+s}$ in the last row of $\Delta^{(rs)}$, so that

$$P_{rs}(x, y) = \frac{1}{\Delta^{(rs-1)}} \begin{vmatrix} \mu_{00} & \mu_{10} & \mu_{01} & \cdots & \mu_{r,s+1} & \mu_{r-1,s} & \mu_{rs} \\ \mu_{10} & \mu_{20} & & & \mu_{r+1,s-1} & \mu_{rs} & \mu_{r+1,s} \\ \mu_{01} & & & & \mu_{rs} & \mu_{r-1,s+1} & \mu_{r,s+1} \\ \cdot & & & & \cdot & \cdot & \cdot \\ \cdot & & & & \cdot & \cdot & \cdot \\ \mu_{r,s-1} & \mu_{r+1,s-1} & \mu_{rs} & \cdots & \mu_{2r,2s-2} & \mu_{2r-1,2s-1} & \mu_{2r,2s-1} \\ \mu_{r-1,s} & \mu_{rs} & \mu_{r-1,s+1} & \cdots & \mu_{2r-1,2s-1} & \mu_{2r-2,2s} & \mu_{2r+1,2s} \\ 1 & x & y & & x^r y^{s-1} & x^{r-1} y^s & x^r y^s \end{vmatrix} \tag{19}$$

It is evident that in virtue of (3),

$$\sum_{i=1}^{N} P_{rs}{}^2(x_i, y_i) = \sum_{i=1}^{N} (x_i{}^r y_i{}^s) P_{rs}(x_i, y_i),$$

and on multiplying through (19) and summing, we find

$$\sum_{i=1}^{N} P_{rs}^2(x_i, y_i) = \Delta^{(rs)}/\Delta^{(rs-1)}, \tag{20}$$

and similarly,

$$\sum_{i=1}^{N} T_i P_{rs}(x_i, y_i) = \Delta_{[rs]}{}^{(rs)}/\Delta^{(rs-1)},$$

where

$$\Delta_{[rs]}{}^{(rs)} = \begin{vmatrix} \mu_{00} & \mu_{10} & \mu_{01} & \cdots & \mu_{r,s-1} & \mu_{r-1,s} & \mu_{00}{}^{(1)} \\ \mu_{10} & \mu_{20} & & & & \mu_{rs} & \mu_{10}{}^{(1)} \\ \mu_{01} & & & & & & \mu_{01}{}^{(1)} \\ \cdot & & & & & & \cdot \\ \cdot & & & & & & \cdot \\ \cdot & & & & & & \cdot \\ \mu_{r,s-1} & & & & & & \mu_{r,s-1}{}^{(1)} \\ \mu_{r-1,s} & \mu_{rs} & & & & \mu_{2r-2,2s} & \mu_{r-1,s}{}^{(1)} \\ \mu_{rs} & \mu_{r+1,s} & \mu_{r,s+1} & \cdots & \mu_{2r,2s-1} & \mu_{2r-1,2s} & \mu_{rs}{}^{(1)} \end{vmatrix}$$

$$\mu_{ab}{}^{(1)} = \sum_{i=1}^{N} T_i(x_i{}^a y_i{}^b)$$

Finally, therefore,

$$b_{rs} = \Delta_{[rs]}{}^{(rs)}/\Delta^{(rs)}. \tag{21}$$

and thus the formulae (21) and (19) complete the specification of $t(x, y)$.

The quantities $Z_{rs}{}^2 = b_{rs}{}^2 \sum_i P_{rs}{}^2$ are analogous (although not necessarily precisely equivalent) to the $z_{rs}{}^2$ terms discussed in connection with the DeLury method. If the residuals are normally distributed the two quantities should have the same statistical properties, and so the procedure is to evaluate the array of $Z_{rs}{}^2$ out to the point where the "break" is evident. Unfortunately, the residual ensemble is not available for general tests of homogeneity, and there is no strict analogy to the test for serial correlation among equally spaced residuals. The coefficients themselves, however, can be tested as before, by referring the statistic

$$t_{rs} = b_{rs}\left[\sum_i P_{rs}{}^2\right]^{1/2}/S$$

to the distribution of t on $N-K-1$ degrees of freedom, if K terms are chosen for the trend. It can easily be shown that

$$S^2 = \sum_{i=1}^{N} T_i{}^2 - \sum^{K} Z_{rs}{}^2$$

where the summation of the Z^2 values extends over those judged to be significant. Generally N will be so large that t_{r_0} may be referred directly to a table of the "critical values" of the normal distribution.

LABOR AND COSTS

The techniques we have discussed so far were chosen particularly for their adaptability to automatic computation. The manipulation of determinants and matrices is a part of the standard repertory of every computing service. Indeed, without the aid of machines the arithmetical labor involved in polynomial fitting would be altogether prohibitive.

With the new IBM No. 650 magnetic drum computer, the total computation costs are far below the salary equivalent of the number of hours or days required of an experienced interpreter to perform essentially the same task by visual methods, such as smoothing contours or profiles. While the writer's experience in the use of grids is very limited, the body of opinion seems to be that these are usually more expensive to use than smoothing methods; and so the cost of polynomial fitting would compare even more favorably. To illustrate this point, let us compare costs for a survey 24 miles square containing about 2,000 stations. This would correspond to an average of slightly more than one station every $\frac{1}{2}$ mile along all section lines. The following estimates have been given by IBM's Scientific Computing Service in New York City for the use of the 650. These figures were received in June, 1955, and of course they may be subject to some change; but they should serve at least as a rough index:

For computing the z^2 array and the coefficients of $t(x, y)$ by the DeLury method with $m=n=25$, $57.

For computing the z^2 array and coefficients of $t(x, y)$ out to $r+s=6$ with $N=2{,}000$, about $75.[8]

The additional cost of evaluating $t(x, y)$ at station locations will be a small fraction of the above figures.

In addition, there is the initial cost of writing and verifying the programs. This occurs only once and may be amortized gradually. To write and to verify both programs (§1 and §6) should cost a total of about $250.

It is difficult to estimate very precisely how much time a skilled interpreter would require to make his analysis by smoothing contours, but this writer believes that unless the regional trend is unusually simple it would take him perhaps a week to do a careful job on a problem of this size. If he takes the approach of smoothing interlocking profiles, he will probably require twice that time.

In addition to the savings in cost, however, there is a very large saving in labor and time; which conceivably might be a dividend of far greater value than the money. Skilled personnel may be freed from the (largely) mechanical labor of analysis, to devote a greater part of their energies and time to the more

[8] Author's estimate from IBM data.

creative work of geological interpretation. Of course, as this writer is only too keenly aware, there cannot be too strict a divorce between analysis and interpretation. Each is bound to have its influence upon the other, and rightly so. There are many who argue—and not without a good deal of persuasive logic—that the analysis of data into "regional" and "residual" components is itself a problem in interpretation, and that the use of a concept or bias is not only legitimate at this stage but even necessary in order to draw the most intelligent picture. Those who subscribe to this point of view will find little satisfaction in the statistical methods presented thus far, for they will note that they are almost wholly objective in outlook, and are possessed of all the advantages and disadvantages that go with objectivity. (It should not be concluded, however, that polynomial fitting gives the same result as "gridding." Those who doubt this statement are advised to try both procedures and compare the results.)

The subject of interpretative bias in statistical analysis, however, is too large and too interesting to be introduced at this point. It deserves a separate and special study.

ACKNOWLEDGMENTS

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APPENDIX

Derivation of the relation (12):

It is assumed that the form of the distribution of L_1 can be approximated by the Pearson Type I distribution

$$p(L_1)dL_1 = [B(p, q)]^{-1}L_1^{p-1}(1 - L_1)^{q-1}dL_1 \tag{1}$$

whose powers p and q are chosen such that the first two sampling moments are correct.

The rth sampling moment of L_1 for k samples, each with $n_i = 1$, about $L_1 = 0$ is (cf. Neyman and Pearson, 1931; Welch, 1936):

$$\mu_r' = k^r \frac{\Gamma\left(\frac{1}{2}k\right)}{\Gamma\left(\frac{1}{2}k + r\right)} \cdot \frac{\Gamma^k\left(\frac{1}{2} + \frac{r}{k}\right)}{\Gamma^k\left(\frac{1}{2}\right)} \tag{2}$$

Thus

$$\mu_1' = 2\left[\frac{\Gamma\left(\frac{1}{2}+\frac{1}{k}\right)}{\Gamma\left(\frac{1}{2}\right)}\right]^k$$

From the Weierstrass definition of the Gamma function

$$\frac{1}{\Gamma(z)} = ze^{\gamma z}\prod_{n=1}^{\infty}\left(1+\frac{z}{n}\right)e^{-z/n}, \qquad \gamma = 0.5772,$$

it follows that

$$\left[\frac{\Gamma\left(\frac{1}{2}+\frac{1}{k}\right)}{\Gamma\left(\frac{1}{2}\right)}\right]^k = \frac{e^{-\gamma}}{\left(1+\frac{2}{k}\right)^k}\prod_{n=1}^{\infty}\frac{e^{1/n}}{\left[1+\frac{1}{\left(n+\frac{1}{2}\right)k}\right]^k}.$$

Noting that, when k is moderately large,

$$\left(1+\frac{\alpha}{k}\right)^k = e^{\alpha} - \frac{1}{k}\sum_{n=2}^{\infty}\frac{n(n-1)}{n}\frac{\alpha^n}{n!} + O\left(\frac{1}{k^2}\right)$$

$$\cong e^{\alpha}\left(1-\frac{\alpha^2}{2k}\right), \qquad \alpha \ll k,$$

it follows that

$$\left[\frac{\Gamma\left(\frac{1}{2}+\frac{1}{k}\right)}{\Gamma\left(\frac{1}{2}\right)}\right]^k \cong \frac{e^{-(\gamma+2)}}{1-\frac{2}{k}}\exp.\sum_{n=1}^{\infty}\left[\frac{1}{n}-\frac{1}{n+\frac{1}{2}}\right] \cdot \prod_{n=1}^{\infty}\left[1-\frac{1}{2k\left(n+\frac{1}{2}\right)^2}\right]^{-1}$$

Now

$$\prod_{n=1}^{\infty}\left[1-\frac{1}{2k(n+1/2)^2}\right] = 1-\frac{2}{k}\sum_{n=3}^{\infty}\frac{1}{n^2}+O\left(\frac{1}{k^2}\right),$$

$$\cong 1-\frac{0.790}{k}, \qquad \text{since } \sum_{n=1}^{\infty}\frac{1}{n^2} = \frac{\pi^2}{6}$$

and so

$$\mu_1' = 2e^{-(\gamma+2)+\beta}\cdot\left(1 - \frac{2.790}{k} + O\left(\frac{1}{k^2}\right)\right)^{-1} \tag{3}$$

where

$$\beta = \sum_{n=1}^{\infty} \frac{1}{n(2n+1)}.$$

Similarly,

$$\begin{aligned}\mu_2' &= \frac{k^2\Gamma\left(\frac{1}{2}k\right)}{\Gamma\left(\frac{1}{2}k+2\right)}\cdot\frac{\Gamma^k\left(\frac{1}{2}+\frac{2}{k}\right)}{\Gamma^k\left(\frac{1}{2}\right)} \\ &= \frac{4}{1+\frac{2}{k}}\cdot\frac{e^{-2\gamma}}{\left(1+\frac{4}{k}\right)^k}\prod_{n=1}^{\infty}\frac{e^{2/n}}{\left(1+\frac{2}{(n+1/2)k}\right)^k} \\ &= 4e^{-2(\gamma+2)+2\beta}\left[1 - \frac{9.160}{k} + O\left(\frac{1}{k^2}\right)\right]^{-1}\end{aligned} \tag{4}$$

It can be shown that

$$\beta = -\int_0^1 \log(1-u^2)du = 2 - 2\log 2 = 0.6137.$$

Thus

$$-(\gamma+2)+\beta = 1.9635, \quad \text{and} \quad e^{-1.9635} = 0.1404.$$

The first and second moments of (1) about $L_1 = 0$ are, respectively,

$$\mu_1' = \frac{p}{p+q} \quad \text{and} \quad \mu_2' = \frac{p(p+1)}{(p+q)(p+q+1)}.$$

We identify these with (3) and (4) and solve algebraically for p and q, obtaining, finally,

$$\frac{p}{k} = 0.201\left(1 - \frac{11.65}{k}\right), \qquad \frac{q}{k} = 0.514\left(1 - \frac{15.53}{k}\right) \tag{5}$$

These formulae neglect terms of order $1/k^2$ and higher; however, for $k \geqq 100$, the error incurred by this omission amounts to less than 1 percent.

The "5 percent" point of L_1 is the root of x in the expression

$$I_x(p, q) = 0.05, \tag{6}$$

where

$$I_x(p, q) \equiv B_x(p, q)/B(p, q) = \frac{\Gamma(p+q)}{\Gamma(p)\Gamma(q)} \cdot \int_0^x L_1^{p-1}(1 - L_1)^{q-1} dL_1 \qquad 0 \leqq x \leqq 1$$

Generally, p and q will both be large enough that the following approximation, due to Cochran (1940), may be used: Fisher's z-transformation of x in (6) is

$$z = \frac{1}{2} \log_e \frac{p(1-x)}{qx}, \qquad x = \frac{p}{p + qe^{2z}} \tag{7}$$

and when $p > 30$, $q > 20$ the distribution of z may be approximated by the normal distribution. Thus the procedure for determining x is as follows: Calculate

$$A = \frac{4pq}{p+q},$$

$$z_\alpha = \frac{y_\alpha}{\sqrt{A - \lambda_\alpha}} + \frac{(\lambda_\alpha - \frac{1}{6})(A - 2p)}{pA} \tag{8}$$

where y_α is the value of the normal deviate with unit variance at the probability level α, and $\lambda = \frac{1}{6}(y^2+3)$. For $\alpha = 0.05$, $y_{.05} = 1.6449$ and $\lambda_{.05} = 0.9509$. Substitute these values and the expressions (5) into (8) to obtain $z_{.05}$, and then substitute this expression into (7) to obtain $(L_1)_{.05}$. The rest is merely algebra.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 345-347

NOTE ON AN APPLICATION OF SONAR TO THE SHALLOW REFLECTION PROBLEM*

ISIDORE ZIETZ† AND L. C. PAKISER†

Modified sonar transducers have been successfully used in water-covered areas to determine depths to the water bottom, layers within the bottom sediments, and depth to bedrock (Smith and Nichols, 1953). The possibility of detecting shallow horizontal beds by placing a sonar transducer directly on the ground is particularly attractive. Velocity discontinuities at depths of several hundred or more feet have long been successfully mapped by means of conventional seismic reflection methods. Recently, reflections from much shallower, closely spaced horizons have been recorded by increasing the filtered frequency range of the amplifiers to an upper limit of 300 to 500 cycles per second, and by other instrumental modifications (Pakiser, Mabey, and Warrick, 1954; Olson, 1955). Evison has recorded still shallower reflections by using an electromechanical vibrator that generates a square-enveloped pulse of sine waves at frequencies of 100 to 800 cycles per second and pulse widths of from 5 to 100 milliseconds (Evison, 1954).

In the summer of 1955, the U. S. Geological Survey conducted preliminary sonic tests in Portage County, Ohio. The field work was supervised by R. E. Warrick and J. W. Berg. Apparent reflections coming from velocity discontinuities a few feet below the surface of the ground to depths as great as 100 feet or more were recorded using a sonar-type transducer placed directly over the ground.

In the Ohio test area, unconsolidated glacial till, coarse glacial outwash materials, and lacustrine and fluviatile deposits of Pleistocene age, as much as several hundred feet thick, overlie a sequence of flat-lying rocks of Devonian and Mississippian age. Good reflections from shallow horizons have already been recorded using small explosive charges and high frequency seismic equipment (Pakiser and Warrick, 1956). Average velocity determinations computed from refraction traveltime curves and drill hole information were available to check reflection times from the sonar source.

The instrument used is a crystal sonar transducer manufactured by the Telephonics Corporation. The signal output is a square-enveloped pulse ranging in length from 1 to 9 milliseconds and containing waves of frequencies 6, 11.5, or 16 kilocycles per second. The transducer is approximately 25 inches in diameter and 18 inches high, weighs close to 300 pounds, and delivers a maximum of 2,500 watts of acoustic power in water. Reflections are permanently recorded on sensitized paper and displayed visually on a cathode-ray tube.

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† U. S. Geological Survey, Washington, D. C.

Because the sonar transducer used was designed for maximum energy transfer into water, there is an acoustic impedance mismatch when it is placed directly over ground. Therefore, it became necessary to find suitable coupling devices to match the transducer acoustically to a weathered layer of low velocity and density that is found above the shallow water table in Portage County. Four different coupling devices were tried:

1. Quarter-wavelength thicknesses of rubbers of different hardness and acoustic impedance. Loose pebbles on the surface were scraped away and a thin film of grease was placed between the rubber and the ground; the transducer was placed on the rubber.

2. Shallow pits filled with a few inches of low-viscosity grease into which the transducer was placed.

3. Shallow pits filled with water into which the transducer was placed.

4. A water-filled, galvanized-steel cylindrical tank about 3 feet high and 3 feet in diameter surrounded by a thin plastic membrane that also formed the bottom of the tank. Again, loose pebbles were removed from the surface before the tank was placed in position and a thin film of grease was placed between the plastic and the ground for more efficient coupling. The transducer was immersed in the water.

The poorest records were obtained where rubber was used as the coupling agent, probably because of the high energy absorption of porous rubber. In general, better penetration of sound energy was observed with a grease-filled rather than a water-filled pit. The best records were obtained where the water-filled tank was used as a coupler, probably in part because the greater head of water in the tank prevented cavitation, resulting in a greater transfer of energy into the ground. Although sound absorption in earth increases with frequency, maximum energy penetration occurred not with a transmitter frequency of 6 kc, but of 11.5 kc. This great penetration at the higher frequency probably occurred because the transducer was designed for maximum power output at 11.5 kc.

The sonar records were similar to those obtained with the transducer immersed completely in a large body of water (Smith and Nichols, 1953). Most of the records displayed many multiple reflections, but there were some seemingly real reflections coming from velocity discontinuities as much as 100 feet deep. When the transducer was placed directly on a bedrock outcrop, reflections from apparent depths of more than 250 feet were observed. Some reflections seem to correlate well with lithologic markers for which hypothetical reflection times had been calculated from seismic uphole times and the known average velocity (5,500 fps) of the water-saturated, near-surface, unconsolidated sediments. However, most of the reflections are unexplained, although they seem to be real events.

At several locations a prominent multiple reflection repeating as many as 17 times with an interval of 5 to 6 milliseconds was noted. It was known, from

seismic refraction data at two of these locations, that the two-way delay time in the weathered layer was almost identically the same (5 to 6 milliseconds). Therefore it was assumed that the multiple reflection represented repeated travel of the acoustic pulse between the surface of the ground and the shallow water table.

Further experiments are planned, using hydrophone receivers placed in drill holes to detect sonic energy from the transducer placed at the surface, acoustic logging for velocity control, improved coupling devices, and transducers designed specially for use on land.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 348–358, 7 FIGS.

SUBMARINE GRAVITY DETAILING, SAN LUIS PASS DOME, BRAZORIA COUNTY, TEXAS*

L. L. NETTLETON†

ABSTRACT

The San Luis Pass shallow salt dome lies about 7 miles offshore from the Texas coast under about 50 feet of water. A detailed submarine gravity survey was made to determine the outline, thickness and depth of caprock as a guide for test drilling for the evaluation of the dome as a sulphur prospect. There were no drilling contacts on the dome when the work was done. Seventeen test wells were subsequently drilled within the shallow dome outline as estimated from analysis of the gravity results. The caprock found was slightly smaller in area, considerably shallower in depth and of substantially the same thickness as predicted. The caprock material is nearly all gypsum.

INTRODUCTION

The San Luis Pass dome, under about 50 feet of water, centers about seven miles off the Texas Coast, southeast of San Luis Pass, about midway between Galveston and Freeport. (San Luis Pass is at the southwest end of Galveston Island). The detailed gravity survey described in this paper was made to determine the area, thickness and depth of the caprock as a guide to test drilling to evaluate the dome as a sulphur prospect.

THE GEOPHYSICAL PROBLEM

The application of gravity surveys to the determination of the principal features of shallow salt domes is not new. Some of the early torsion balance surveys, made over thirty years ago, were for this purpose. Several such surveys have been described by Barton, (1948). The possibility of accomplishing the same result with closely spaced gravity meter observation of high precision appears to have had little appreciation. From the time of Barton's work, prior to 1937, to the detailed gravity meter survey over the Pine Prairie dome (Nettleton, 1956) which was done in 1953 and the somewhat earlier detailed survey over the Moss Bluff dome (Hammer, 1955), any gravity detailing of shallow domes was not made public. During this long interval the gravity meter reached a high degree of precision and reliability and was applied, mostly in reconnaissance surveys, in many parts of the world, including a great deal of work in the Gulf Coast salt dome belt.

It has been pointed out many times that the determination of geologic structure from gravity data is ambiguous without the use of other information. See, for instance, Nettleton (1940), page 119. In the case of the San Luis Pass dome, the ambiguity problem is particularly pertinent because no data on the dome, other than its general location, were available when the survey was made. How-

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ever, the ambiguity was considerably reduced by general knowledge of the probable density contrasts and of the form and behavior of Gulf Coast domes which had been obtained from other similar surveys over domes where considerable information was available from drilling. From this experience the problem of determining the essential features of the dome from a gravity survey of adequate detail and precision was approached with considerable confidence.

In planning the survey, two different aspects of the problem had to be considered. First, there must be a sufficient density of stations over and immediately around the expected area of the shallow part of the dome to determine the nature of the sharp gravity changes from any shallow salt or caprock. Second, the gravity control must extend far enough to determine the regional effects and, at least approximately, the relatively wide-spread effects of the deep salt column.

THE GRAVITY OBSERVATIONS

The survey was carried out with a LaCoste-Romberg underwater gravity meter with readings made by remote control with the meter on bottom. The meter was carried on the motor vessel GMX II, a converted 104 ft, twin-screw sub-chaser.

The water depth over the area of the survey varies from 40 to 55 ft. Water depth was determined by a pressure tube attached to the electric cable with its open end at the meter. The tube leads to an air reservoir on the boat which is charged with an excess air pressure after the meter is on bottom. Carefully calibrated pressure gauges read the equilibrium pressure after the excess bleeds off through the tube to the meter and the depth is calculated from this pressure. Water depths thus determined are accurate to about 0.1 ft. Elevations are calculated from water depths by making a tidal correction determined from variation in water depths at the base stations.

The boat was not anchored for reading the meter. An anchored marker flag, thrown overboard at each station, serves as a reference by which the boat is kept near the station by manipulation of engine throttles, clutches and rudder.

The observations were reduced in the usual manner, with latitude corrections, elevation corrections with a factor of .071 mg/ft (corresponding to a density of 1.8) and a correction for the upward attraction of the water over the meter. This amounts to reducing the stations to sea level elevation as if they were made on the ground with the water absent.

POSITIONING THE GRAVITY SURVEY

At the time the San Luis Pass survey was laid out, the approximate location of the dome was known from the areas of lease purchases and from the Shell well which was known to be on the west flank of the dome, but which found no dome material to its total depth of 7,629 ft. Since the area to be covered is all within about 12 miles of the coast, it was decided to locate the stations by transit observations to a light on the boat, the work being done at night (February,

1955). Contact with the boat was maintained with two-way radios on the boat and at each transit. The station locations were controlled from three U.S.C. & G.S. triangulation stations conveniently located along the beach opposite the dome. (see index map, Figure 1). The desired station locations were preplotted and the bearings determined from the three triangulation stations or from "hubs" along the beach opposite the lines of gravity stations.

The detailed gravity stations in the central part of the survey, where precise location was particularly necessary, were laid out in a fan from the central triangulation station, "Tatlum." The transit on this station could keep the boat on the line. Transits on the two lateral triangulation stations set off the angles for the successive stations on the line and called the boat to stop when the positions were reached. When the meter was on bottom, the three transits each read the bearing for final plotting of station locations.

This general operation was carried out without difficulty and the results were

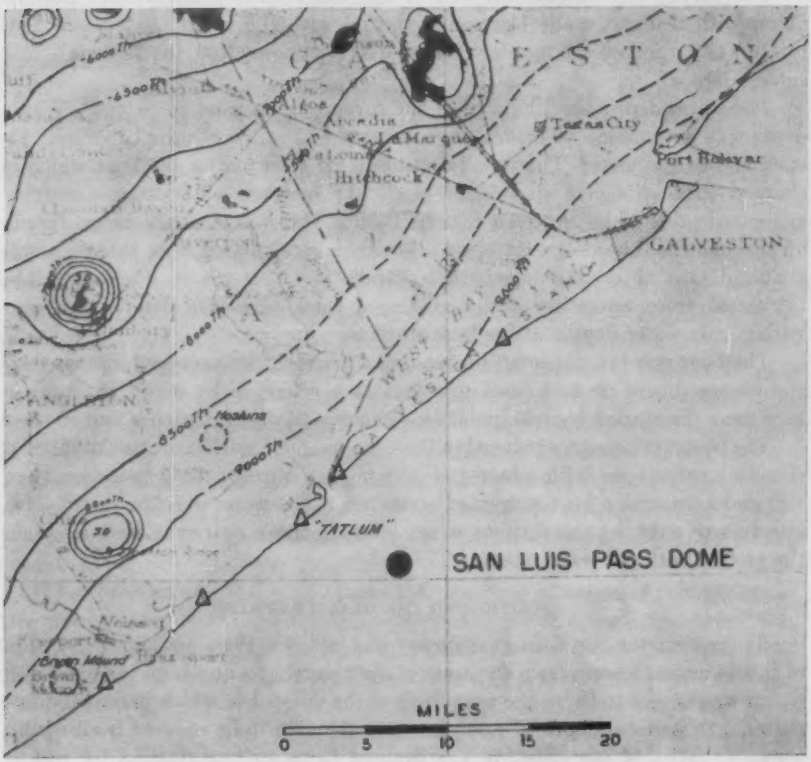


FIG. 1. Index map showing location of San Luis Pass dome.

quite satisfactory. Station spacing varied from about 1,500 ft immediately over and around the area of the expected dome to 5,000 ft in the outer parts of the survey. The total number of stations was 129, of which 81 were in the central area of detailing. The survey extends to a maximum distance of 26,000 ft from the center of the dome.

RESULTS OF THE SURVEY

The observed gravity map resulting from the survey is shown by Figure 2. The dome picture is partially masked by the very strong southeasterly gravity increase, but the sharp local disturbances clearly show the presence of a shallow dome.

For quantitative evaluation it is necessary to isolate the positive anomaly from the negative effect of the underlying salt column and from the strong regional background. The negative effect of the salt and the regional were evaluated by a series of profiles across the survey area. This "regional plus salt" effect and the positive anomaly remaining after its removal are shown by Figure 3.

This picture shows clearly a slightly elliptical positive anomaly from the shallow part of the dome. The maximum relief of this isolated positive effect is 2.6 mg.

CALCULATION OF THE DOME FORM

Estimates of depth, thickness and shape of any caprock had to be based entirely on the gravity results and on general geological conditions because no drilling contacts on the dome were available. The values for density contrasts were extrapolated from previous experience in calculating Gulf Coast domes where more information was available. This is a critical question because it would be possible, with quite reasonable values for the density of salt and of the laterally adjacent sediments at shallow depth, to account for the positive gravity effect by shallow salt without the assumption of any caprock at all.

The essential features of the separation of the total or observed gravity effect into its several components are indicated, Figure. 4, by the following curves:

(1) the observed gravity profile along the northeasterly line shown on Figures 2 and 3;
(2) the regional gravity profile;
(3) the residual gravity profile after subtraction of this regional;
(4) the estimated negative effect due to the salt column;
(5) the positive residual after subtraction of this negative salt effect;
(6) the calculated positive effect of the shallow part of the dome.

The lower part of the figure shows a cross section of the dome, as finally calculated, with the projected position of three wells. The Shell well was drilled before the work was done but its relation to the dome, other than that the dome was not reached, was unknown; the two Humble wells were drilled after the gravity survey and analysis.

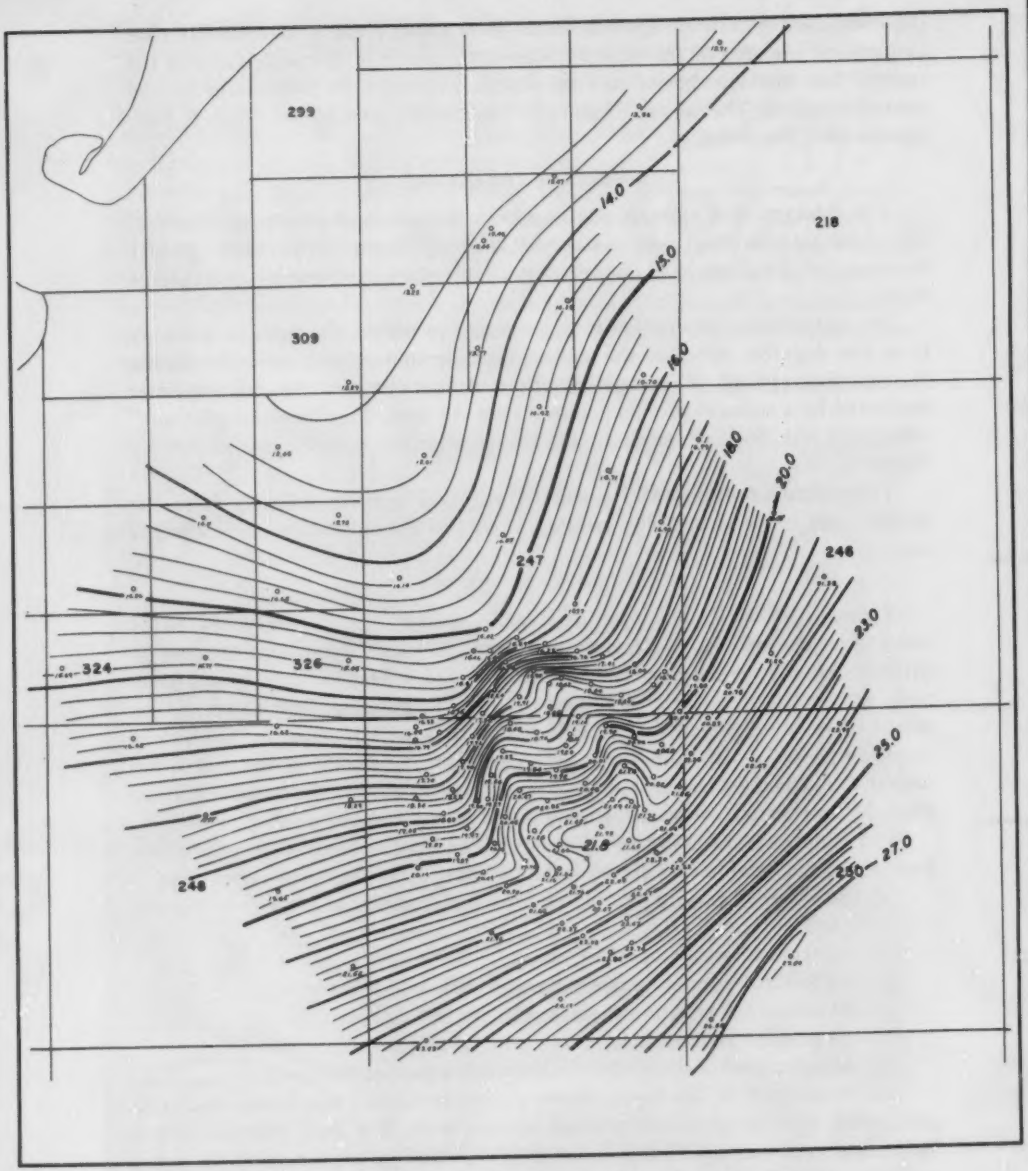


FIG. 2. Observed gravity map. Contour interval 0.2 mg.

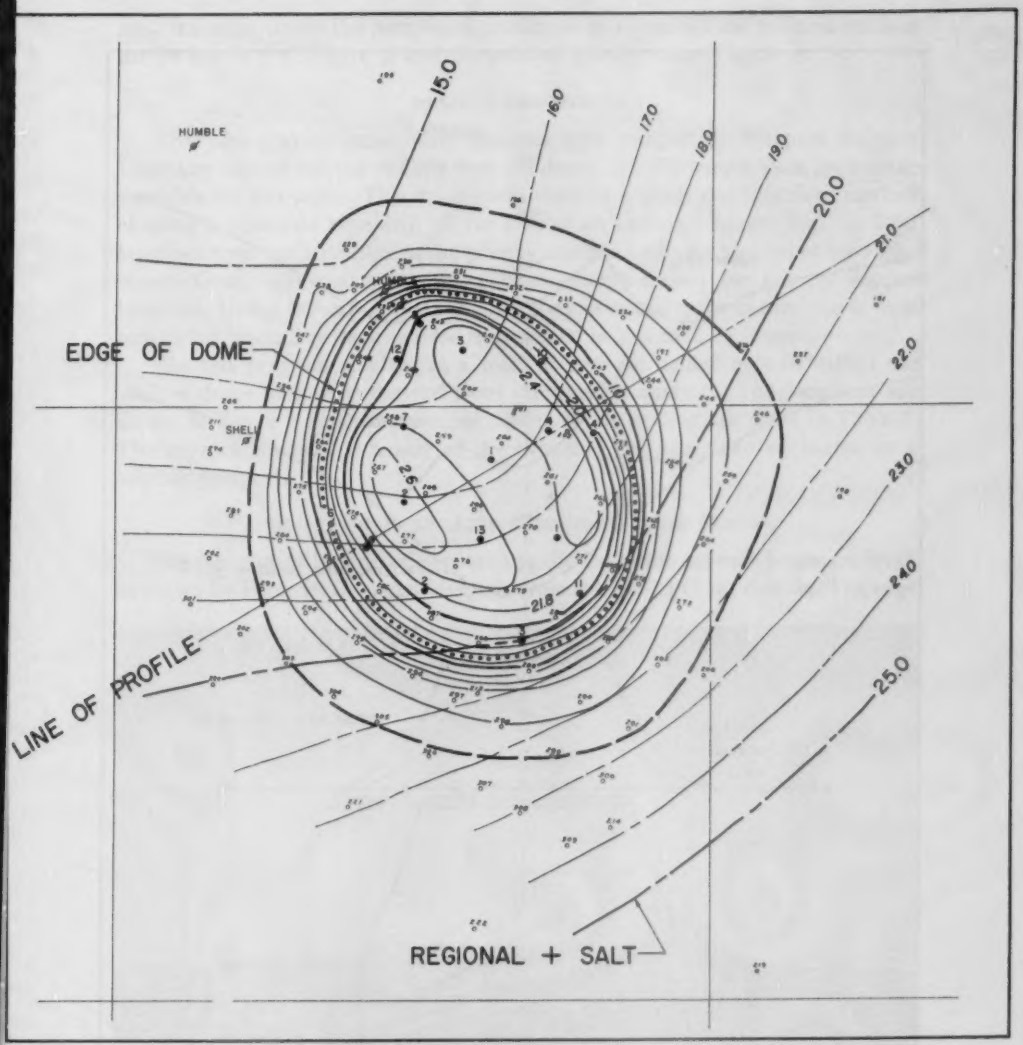


FIG. 3. Positive residual gravity map. Contour interval 0.2 mg.

The shallow part of the dome, as determined from the gravity analysis, is elliptical in form, as shown by the dotted line on Figure 3, with dimensions of about 7,000 by 9,000 ft. The estimated caprock thickness was about 200 ft. The estimated maximum depth was about 400 ft in the center and slightly shallower

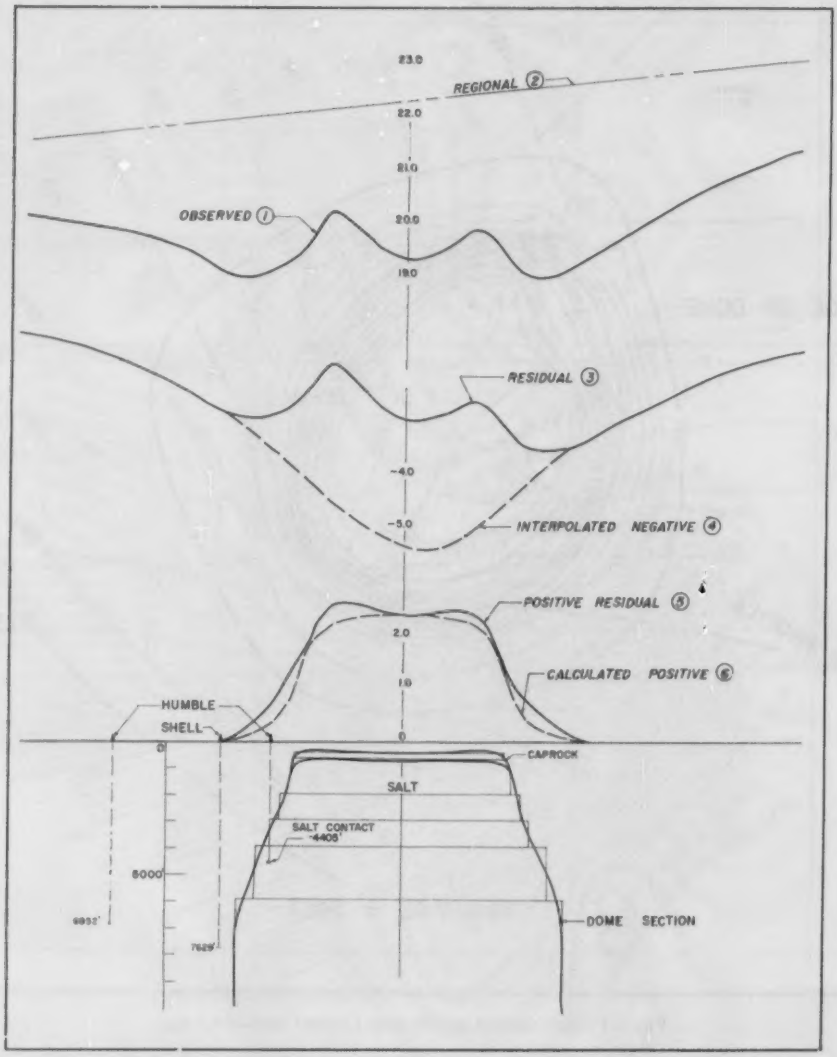


FIG. 4. Gravity profiles and dome cross section on profile line of Figs. 2 and 3.

near the edge, under the peripheral maximum as shown by the positive residual profile (curve 5 of Figure 4) and the residual gravity map (Figure 3).

RESULTS OF DRILLING

After the gravity survey and analysis were completed, Freeport Sulphur Company carried out test drilling over the dome, and the results have been made available for this paper. This drilling was done by a novel and ingenious method of using a shot-hole type drill off the side of an anchored barge (Fig. 5). Drill locations were made relative to the gravity stations and were positioned by visual observations from the same triangulation stations used for gravity station locations. Under favorable weather conditions wells to depths of over 300 ft were completed (including moving time to location) in less than 24 hours.

The test program resulted in a total of 17 wells drilled on and within the shallow dome outline as derived from the gravity analysis. The locations are shown in Figure 6 and the principal results of the drilling are listed in Table I. The caprock material is nearly all gypsum and the dome proved barren as a sulphur prospect.

COMPARISON OF DRILLING RESULTS WITH PREDICTIONS

The contours of Figure 6 show depth to the top of the caprock below sea level, as drawn by Freeport Sulphur Company from the results of the drilling. The edge

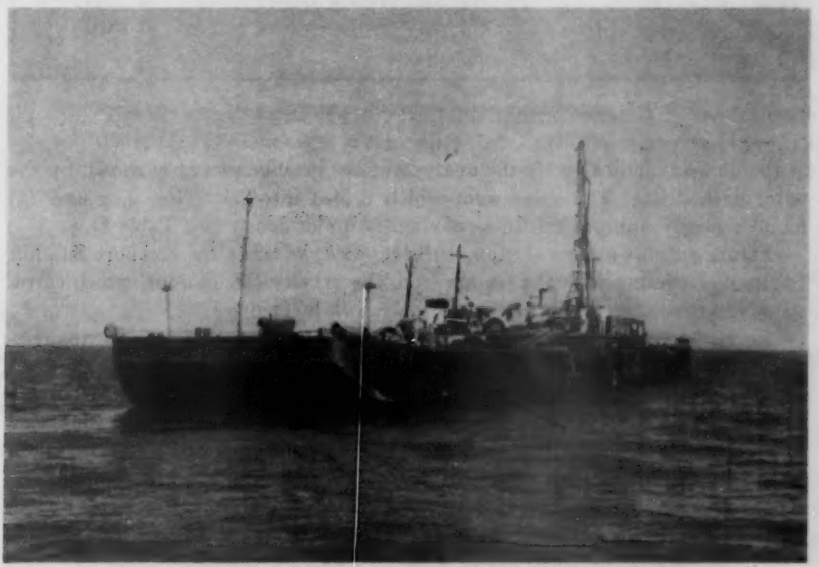


FIG. 5. Barge and rig used for test drilling (courtesy Freeport Sulphur Company).

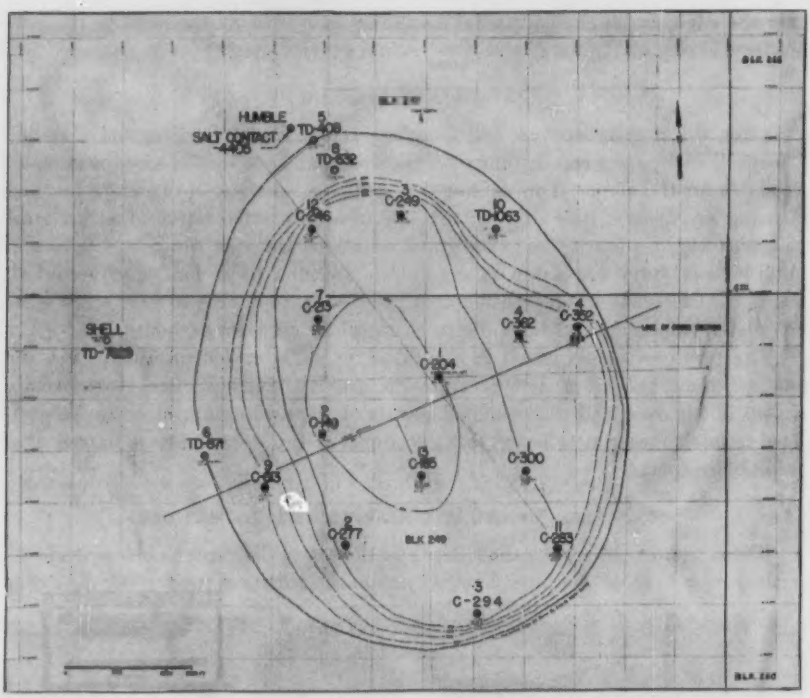


FIG. 6. Test wells and contours on top of dome (courtesy Freeport Sulphur Company).

of the dome as indicated by the analysis of the gravity survey is shown by the outer dashed line. The three wells which drilled into salt (Nos. 4, 7 and 13) found a nearly uniform thickness of slightly under 200 ft (see Table I).

Figure 7 shows a cross section of the caprock, as made by Freeport Sulphur Company, together with the section from the gravity calculations, which corresponds to the caprock part of the section shown in Figure 4.

From the comparison indicated by Figures 6 and 7 we find the following relations between the predictions from the gravity analysis and the actual shallow dome as revealed by the drilling:

(1) The predicted general location, size and shape are substantially confirmed but the actual dome is a little inside the predicted outline. The largest discrepancy is at well No. 10, on the northeast flank, which is about 600 ft inside the predicted "edge" and found no dome material to 1,063 ft. Also, on the north flank, well No. 8, about 700 ft inside the edge, found no dome material to 632 ft.

(2) The depth of the caprock is considerably less than was anticipated. The

TABLE 1

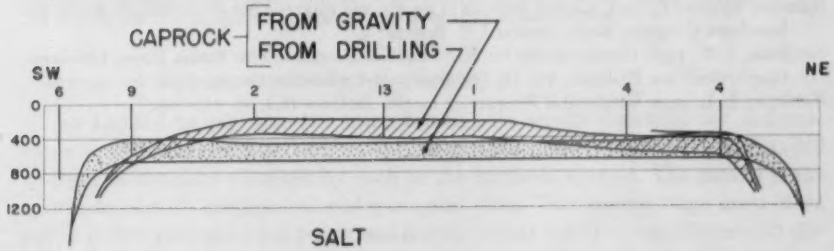
TEST WELLS—SAN LUIS PASS DOME

All figures in feet, depths are from water surface

No.	water depth	cap	salt	T.D.	cap thickness	cap material
S-1	51	204	—	210	6′+	porous gypsum
S-2	49	149	—	166	17′+	porous gypsum
S-3	50	249	—	203	14′+	porous gypsum
S-4	50	362	—	369	7′+	gypsum
E-1	48	300	—	358	58′+	massive gypsum
E-2	50	277	—	286	9′+	massive gypsum
E-3	50	294	—	358	64′+	9′ calcitic limestone 55′ massive gypsum
E-4	49	352	542	358	190′	massive gypsum
E-5	46	—	—	408		no dome material
E-6	50	—	—	871		no dome material
E-7	53	213	408	429	195′	massive gypsum
E-8	48	—	—	632		no dome material
E-9	50	613	—	624	11′+	massive gypsum
E-10	49	—	—	1,063		no dome material
E-11	49	283	—	300	97′+	massive gypsum
E-12	48	234	—	261	27′+	hard gypsum
E-13	49	165	358	368	193′	gypsum

cross section from the gravity calculation is about 400 ft deep at the center and about 350 ft under the peripheral maximum. The actual minimum depth is only 100 ft (below the bottom of the water) at well No. 2, just west of the center. Discrimination within these limits could not be expected with the station spacing of about 1,500 ft in the detailed part of the survey.

(3) The average thickness of caprock found in the three tests drilled into salt was 193 ft. The thickness in the central part of the dome, derived from the the gravity calculations, was 200 ft.



SAN LUIS PASS DOME

FIG. 7. Comparison of predicted and actual caprock section (line of section shown on Fig. 6).

THE SALT COLUMN

The primary objective of the gravity survey and its analysis was the determination of the caprock. The evaluation of the salt column was incidental. However, an approximate determination of the average diameter of the salt column at depth was made to determine the estimated negative salt effect (curve 4 of Figure 4) as shown in the cross section of Figure 4.

At the time the survey was made. the Shell well on the west flank had been drilled to 7,629 ft without finding salt. The Humble well, on the north flank was drilled subsequently and found salt at 4,405 ft (below the water bottom). This well is shown on Figure 4, with its position projected around the dome parallel with the residual gravity contours of Figure 3. The actual salt contact is a little deeper than was anticipated, indicating that the salt cross section of Figure 4 is a little too wide.

It is quite probable that if a more extensive survey were available, to give better evaluation of regional effects, there would have been a better estimate of the salt column. However, such a wide survey was not considered necessary to determine the shallow caprock effect which was the objective of the exploration program.

ACKNOWLEDGEMENTS

The author is particularly grateful to Freeport Sulphur Company for granting permission to publish the results of the gravity survey and analysis and for furnishing the results of the test drilling. Thanks are due also to Shell Oil Company and to Humble Oil & Refining Company for furnishing exact locations and depth data on their wells on the flanks of the dome.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 359–383, 7 FIGS.

A NEW METHOD FOR INTERPRETATION OF AEROMAGNETIC MAPS: PSEUDO-GRAVIMETRIC ANOMALIES*

V. BARANOV†

ABSTRACT

The purpose of this paper is to describe a method of interpretation based on a transformation of the total magnetic intensity anomalies into simpler anomalies. The result of this transformation is the elimination of the distortion due to the obliquity of the normal magnetic field, so that the resulting anomalies will be located on the vertical of the disturbing magnetized bodies.

The starting point of the theory is the well known relation between magnetic potential V and Newtonian potential U—relation which can be written:

$$\vec{\mathfrak{I}} \cdot \overrightarrow{\text{grad}}\, U = f\sigma \cdot V$$

with:

$\vec{\mathfrak{I}}$ = magnetization

$f = 66.7 \cdot 10^{-9}$ $u \cdot CGS$

σ = assumed density of magnetized bodies

This relation may be considered as a partial differential equation. The boundary condition consists in the measured values of the total field $T(P)$ known at each point P at the datum plane. As $T(P)$ is the derivative of a harmonic function V, we can determine this function everywhere above the datum plane. Solving then the partial differential equation, we find the Newtonian potential U and its vertical derivatives $g, g', g'' \cdots$.

Finally, we obtain these quantities as functionals of the measured magnetic anomaly $T(P)$. For instance, one of the formulas is

$$g(M) = \frac{1}{2\pi} \iint H(M, P) T(P) dS_P$$

where $H(M, P)$ is the kernel of the transformation allowing the direct computation of $g(M)$—an anomalous field which will be called "pseudo-gravimetric anomaly."

Of course, the pseudo-gravimetric anomaly has all the usual properties of a gravimetric anomaly. The field of $g(M)$ presents no distortion and the interpretation becomes as easy as that of a Bouguer anomaly map.

To perform the actual routine calculations of this transformation, we start with the values of T taken on a rectangular or trigonal grid, as for the usual computation of the vertical derivatives. The use of punched-card equipment speeds up considerably these calculations.

I. INTRODUCTION

In applied geophysics, the interpretation of results assumes two different aspects, corresponding to two successive phases. The first phase is a detailed analysis of the data obtained by each of the methods applied. The second is the synthesis of both geophysical and geological data. This second stage most often concerns the geologist: the geophysicist only points out the possibilities and discards the inconsistent assumptions, but the first preliminary phase is the geophysicist's concern only.

In gravimetry, the main problem of the preliminary step is the elimination

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of the regional anomaly. Modern methods, computation of the vertical derivatives of the field, are justified only because of their objectivity. But, in magnetic work, the preliminary phase becomes very important.

As a matter of fact, the results of a magnetic survey are more difficult to interpret than those of a gravimetric survey. While, in gravimetry there is a simple connection between the residual anomalies and the tectonic features, in magnetism the anomalies do not take place at the apex of the disturbing bodies. The magnetic picture of the tectonic occurrences undergoes a distortion, due to the inclination of the magnetizing vector.

The difficulty is further increased in the case of an aeromagnetic survey. Then, instead of the vertical component of the field, the variations of the total magnetic field are recorded, and this again increases the distortion of the map: the effects of the obliquity of the recorded field are added to those of the inclination of the magnetization.

An additional difficulty arises at the final stage of the interpretation, when one tries to check the geological assumptions and to compare them, for instance, with a simple typical case. In gravimetry, the computation of the influence is quite immediate; in magnetism, the computation is much more complicated and a greater number of variable factors must be taken into account, such as the inclination of the normal field, the orientation of the structure with respect to the magnetic meridian, and so on.

These considerations show that, when faced with a problem of magnetic interpretation, it is advantageous, to begin with, to transform the isanomal map, in order to suppress the distortion, and to make the map as clear as a map of the Bouguer anomalies.

The purpose of this paper is to show that such a transformation is possible. It is not more difficult than the computation of vertical derivatives, and can be carried out as a routine job. The transformation is based on the fact that, in most practical cases, the magnetic potential V is connected to a gravimetric potential U. We shall first establish this relation.

II. FUNDAMENTALS OF THE METHOD

The gravimetric potential is a Newtonian potential, the general expression of which is

$$U = -f \iiint \sigma \frac{1}{r}\, dv$$

where f is the gravitational constant and σ the density, varying, in general, from point to point. The expression of the magnetic potential can be written as

$$V = \iiint \vec{\mathfrak{I}} \cdot \overrightarrow{\operatorname{grad}} \left(\frac{1}{r}\right) dv$$

where $\vec{\mathfrak{I}}$ is the magnetization vector, which may be variable too. The only assumption that we shall make is to suppose that the direction of $\vec{\mathfrak{I}}$ is the same in all mag-

netized masses. But we are not obliged to assume that this direction is the same as that of the normal terrestrial magnetic field.

Computing the scalar product of the magnetization $\vec{\mathfrak{J}}$ by the gradient of the gravimetric potential, we get the following relation:

$$\vec{\mathfrak{J}} \cdot \overrightarrow{\text{grad}}\, U = f\sigma V.$$

This formula seems to be known since Poisson's time. Let us recall that the founder of applied gravimetry, Eötvos, used Poisson's theorem to deduce two famous relations between the three components of the magnetic anomaly, and the values recorded on a torsion balance, but, now, the Eötvos' formulae are only of historical interest. However, the relation between the two potentials may be used to deduce more practical formulae, allowing direct transformation of the experimental magnetic anomalies into simpler anomalies, which we propose to call "pseudo-gravimetric" anomalies.

There are two reasons for this name: first we do not know the true density σ. Secondly, only the magnetized masses contribute to the potential U. The unmagnetized rocks do not show. Thus the anomalies deduced from U are not the true gravimetric anomalies: they are still magnetic anomalies, but computed on the assumption that the magnetization vector is vertical. To be perfectly clear, we call them "pseudo-gravimetric anomalies."

The essential fact is that anomalies deduced from U are as simple as Bouguer anomalies. They are located on the vertical of the magnetized masses, and do not depend on the inclination of the normal field, nor on the direction of the magnetization. Thus the interpretation and all the computations become very simple, as these factors no longer need to be taken in account.

Therefore, we shall select a conventional density, by writing:

$$f\sigma = |\mathfrak{J}|.$$

Then, calling $\vec{\nu}$ the unit vector representing the direction of $\mathfrak{J}$, we obtain:

$$\vec{\nu} \cdot \overrightarrow{\text{grad}}\, U = \frac{dU}{d\nu} = V \qquad (2\text{-}1)$$

which means that the magnetic potential is the oblique derivative of the pseudo-gravimetric potential, in the direction of the magnetization.

III. TRANSFORMATION OF THE VERTICAL MAGNETIC COMPONENT

Let us now take the upward vertical as the Oz axis, and differentiate the relation (2-1) with respect to z. Thus:

$$\frac{dg}{d\nu} = Z \qquad (3\text{-}1)$$

i.e., the vertical component Z of the magnetic anomaly is the derivative of the

pseudo-gravimetric anomaly, that we shall call g, as in gravimetry, as there is no risk of confusion.

Before dealing with our main problem—the transformation of the anomalies of the total force—let us consider the equation (3-1), which we propose to integrate.

Let us consider (Fig. 1) a straight-line (D), with its origin at M and extending towards infinity, either in the direction of the vector $\vec{\nu}$, or in the opposite direction,

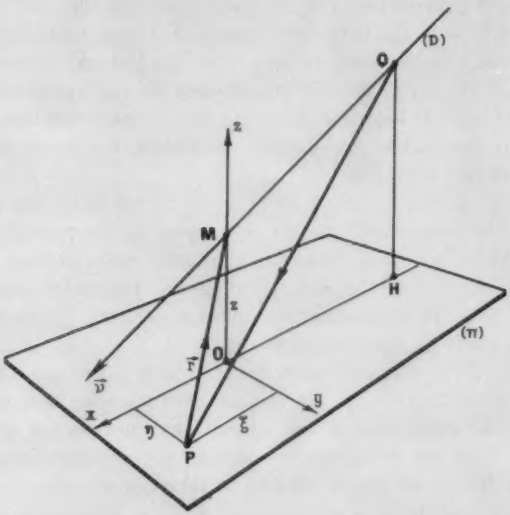

FIG. 1

but in such a manner that (D) will not cross zones where magnetized masses may have a chance to be found. More specifically, let us consider the northern hemisphere. The unit vector $\vec{\nu}$, then, will, in most cases, be directed downwards. We shall take for (D) the half-line with direction opposite to $\vec{\nu}$. It will be in totality above the earth's surface. Let us call Q any given point of this line.

To obtain the function $g(M)$ from (3-1), we need only to integrate this expression along the line (D). We get:

$$g(M) = \int_0^\infty Z(Q)ds$$

where s is the length of the variable sgement $\overline{MQ}$. This is an inverse operation with respect to the derivation in the direction of the vector $\vec{\nu}$. Of course, we do not know the value of the anomaly $Z(Q)$ on line (D). We only know the values of Z measured on the plane (π).

However, it is possible to compute Z at every point Q above the horizontal plane (π), using the well known upward continuation formula. If P is a point of the plane, $Z(Q)$ is given by the expression:

$$Z(Q) = -\frac{1}{2\pi}\iint_{\pi} \frac{\partial}{\partial z}\left(\frac{1}{\overline{QP}}\right) Z(P)\,dS_P$$

where dS_P is a surface element, the integration comprising the whole area of plane (π). Using this value of $Z(Q)$ and changing the order of integrations, we obtain:

$$g(M) = -\frac{1}{2\pi}\iint_{\pi} Z(P)\,dS_P \int_{\pi}^{\infty} \frac{\partial}{\partial z}\left(\frac{1}{\overline{QP}}\right) ds.$$

Let us put in evidence the function

$$K(M, P) = -\int_0^{\infty} \frac{\partial}{\partial z}\left(\frac{1}{\overline{QP}}\right) ds. \tag{3-2}$$

This is the kernel of the linear transformation

$$g(M) = \frac{1}{2\pi}\iint_{\pi} K(M, P) Z(P)\,dS_P \tag{3-3}$$

allowing direct passage from the anomaly of the vertical component Z to the pseudo-gravimetric anomaly $g(M)$ at any given point M above the plane (π).

The formula (3-2) suggests that the kernel K is the derivative, with respect to z, of an harmonic function that we shall denote by $u(M, P)$ and which will be useful hereafter. Thus we shall write

$$K(M, P) = \partial u(M, P)/\partial z \tag{3-4}$$

However, we cannot invert the two operations—integration and derivation with respect to z—because the integral dealing with the reciprocal of the distance $1/\overline{QP}$ is divergent. To remove this difficulty, we shall substitute to this function the following difference:

$$\frac{1}{\overline{QP}} - \frac{1}{s + s_0}$$

where s_0 is an adequate positive constant. If now we take the derivative with respect to this variable, the additional term, independent from z, disappears, while the integral

$$u(M, P) = \int_0^{\infty} \left(\frac{1}{s + s_0} - \frac{1}{\overline{PQ}}\right) ds$$

becomes absolutely convergent, as

$$\frac{1}{s+s_0} - \frac{1}{\overline{QP}} = O(s^{-2})$$

and the differentiation under the integral sign is justified.

The final integration is an elementary one. We easily obtain

$$u = \operatorname{Log}(r + \vec{\nu}\vec{r}) - \operatorname{Log} 2s_0 \tag{3-5}$$

where $\vec{r} = \overrightarrow{MP}$ is the vector from M to P, and

$$r^2 = \xi^2 + \eta^2 + z^2.$$

We chose the origin of coordinates $Oxyz$ on the plane (π), so that point M, of elevation z, is on the vertical axis. The coordinates of point P are ξ, η, o.

Last, to get K, we need only to take the derivative of u with respect to z. We have:

$$K(M, P) = \frac{1}{r}\,\frac{z+\mu r}{r+\vec{\nu}\vec{r}} \tag{3-6}$$

where μ is the cosine of the acute angle between the vector $\vec{\nu}$ and the axis Oz.

We can easily check that $u(M, P)$ are two functions the Laplacian of which is zero (except on D).

The formulae (3-3) and (3-6) completely solve the problem of the transformation of the anomalies of the vertical component into pseudo-gravimetric anomalies.

IV. TRANSFORMATION OF THE TOTAL FORCE

We shall now consider the anomalies of the total magnetic force T.

Let us call $\vec{\gamma}$ the unit vector in the direction of the normal terrestrial field. The anomaly T is the derivative, with the inverse sign, of the magnetic potential V, in the direction $\vec{\gamma}$

$$T = -\frac{dV}{d\gamma}.$$

Thus, taking in account the fundamental relation (2-1) we have

$$T = -\frac{d^2U}{d\gamma dv}. \tag{4-1}$$

Let us now compare this relation with the (3-1) formula. It can be noticed that, here, g is replaced by $-dU/d\gamma$ and Z by T. Thus, without repeating the whole reasoning, we can use the (3-3) formula and write

$$-\frac{dU}{d\gamma} = \frac{1}{2\pi}\iint K(M, P)T(P)dS_P.$$

After differentiating with respect to z, we get, with the usual conventions[1]

$$-\left(\frac{dg}{d\gamma}\right)_M = \frac{1}{2\pi}\iint \frac{\partial K(M, P)}{\partial z}\, T(P)dS_P.$$

To obtain g, of course, we must integrate again along the half-line, the direction of which is, now given by $\vec{\gamma}$ instead of $\vec{\nu}$. We shall get then

$$g(M) = \int_0^\infty \left(\frac{dg}{d\gamma}\right)_Q dS.$$

Let us use the expression of the derivative in the preceding formula, after substituting the variable point Q for M. If we invert the order of the integrations, we obtain:

$$g(M) = -\frac{1}{2\pi}\iint_\sigma T(P)dS_P \int_0^\infty \frac{\partial K(Q, P)}{\partial z}\, ds.$$

We shall put

$$H(M, P) = \int_0^\infty \frac{\partial K(Q, P)}{dz}\, ds \tag{4-2}$$

$$g(M) = -\frac{1}{2\pi}\iint_\sigma H(M, P)T(P)dS_P. \tag{4-3}$$

This latter formula makes it possible to pass from the anomaly of the total force to the pseudo-gravimetric anomaly. The kernel of the transformation $H(M, P)$ is given by (4-2) where the integral is extended along the half-line of direction $-\vec{\gamma}$, while K depends on $\vec{\nu}$.

It is known that in practice one can very often assume that the direction of the magnetization of the underground is that of the normal terrestrial field. Thus, we can assume that the unit vectors $\vec{\gamma}$ and $\vec{\nu}$ are identical. Our aim was to show that this simple assumption is not indispensable to carry out the transformation. However, hereafter, we shall put $\vec{\gamma}=\vec{\nu}$, to simplify the theory and to shorten the computations.

Before computing the kernel H, let us put

$$H(M, P) = \frac{\partial v(M, P)}{\partial z} \tag{4-4}$$

for the formula (4-2) suggests that H is the derivative with respect to z of a function that we call $v(M, P)$. But, before integrating with respect to s, we must subtract the principal part $\mu/(s+s_0)$ from $K(M, P)$, so that the kernel may be integrated. We get

$$v(M, P) = rK(M, P) - \mu u(M, P). \tag{4-5}$$

[1] The anomaly is considered as positive when it increases the recorded value.

The expression of the kernel $H(M, P)$ can be obtained in differentiating with respect to z as indicated in (4-4). However, we shall not need this general expression, as the only thing we are concerned with is the anomaly in plane $z=0$. We shall thus consider what become the kernels K and H at the limit, for $z=0$.

It will be convenient to choose the axis of coordinates so that the Ox axis will be directed towards the magnetic North, and to use polar coordinates, putting

$$\xi = \rho \cos \omega, \qquad \eta = \rho \sin \omega.$$

Then, if we call I the inclination of the normal field, we shall have $\mu = \sin I$. For practical purposes, we shall write $\lambda = \cos I$. We then obtain:

$$r + \vec{\nu} \cdot \vec{r} = \sqrt{\rho^2 + z^2} + \mu z + \lambda \rho \cos \omega$$

and therefore

$$u = \operatorname{Log} [\sqrt{\rho^2 + z^2} + \mu z + \lambda \rho \cos \omega]$$

and

$$K = \frac{1}{\sqrt{\rho^2 + z^2}} \; \frac{\mu \sqrt{\rho^2 + z^2} + z}{\sqrt{\rho^2 + z^2} + \mu z + \lambda \rho \cos \omega}.$$

For $z=0$, these two functions become

$$u = \operatorname{Log} \rho + \operatorname{Log} (1 + \lambda \cos \omega) \tag{4-6}$$

and

$$K = \frac{1}{\rho} \; \frac{\mu}{1 + \lambda \cos \omega}. \tag{4-7}$$

The kernel K is the product of the factor $1/\rho$ by the function of ω alone

$$L_1(\omega) = \frac{\mu}{1 + \lambda \cos \omega}. \tag{4-8}$$

The factor $1/\rho$ is infinite for $\rho=0$, thus K presents a singular point at the origin. However, as $dS = \rho \cdot d\rho \cdot d\omega$, this factor disappears under the sign sum (3-3) and the integral

$$g(0) = \frac{1}{2\pi} \int\int Z(\rho, \omega) L_1(\omega) d\rho \cdot d\omega \tag{4-9}$$

giving the value of the pseudo-gravimetric anomaly at the origin of the coordinates includes no singular element.

Let us now consider the integral (4-3). Differentiating (4-5) with respect to z, and taking in account (3-4), we get

$$H = \frac{z}{r} K + r \frac{\partial^2 u}{\partial z^2} - \mu K. \tag{4-10}$$

The first term is null for $z=0$, the last one has been already computed. To compute the second derivative of u, we should remember that u is harmonic. Therefore,

$$\rho \frac{\partial^2 u}{\partial z^2} = -\frac{\partial}{\partial \rho}\left(\rho \frac{\partial u}{\partial \rho}\right) - \frac{1}{\rho}\frac{\partial^2 u}{\partial \omega^2} = \frac{1}{\rho}\frac{\lambda(\lambda + \cos\omega)}{(1 + \lambda\cos\omega)^2}$$

which is obtained immediately from (4-6). At last, we have:

$$H(\rho, \omega) = \frac{1}{\rho}\cdot\Omega_2(\omega) \tag{4-11}$$

with

$$\Omega_2(\omega) = \frac{(\lambda^2 - \mu^2) + \lambda^3\cos\omega}{(1 + \lambda\cos\omega)^2} \tag{4-12}$$

and hence

$$g(0) = -\frac{1}{2\pi}\iint T(\rho, \omega)\Omega_2(\omega)d\rho\cdot d\omega. \tag{4-13}$$

This integral enables the computation of the pseudo-gravimetric anomaly at the origin of the coordinates: it is a functional of the anomaly of the total force T.

V. DEVELOPED FORMULAE OF THE KERNELS

For the actual computation of the integrals, we shall be obliged to develop the functions K, H, L_1 and Ω_2 into Fourier's series.

Let us start from the well known series

$$\frac{1 - a^2}{1 + 2a\cos\omega + a^2} = 1 + 2\sum_{k=1}^{\infty}(-a)^k\cos k\omega$$

and write

$$a = \eta\frac{r - z}{\lambda} \quad \text{with} \quad \eta = \frac{1 - |\mu|}{\lambda}.$$

The development of (3-6) will be easily found:

$$K = \frac{1}{r} + \frac{2}{r}\sum_{k=1}^{\infty}(-\eta)^k\left(\frac{r - z}{\rho}\right)^k\cos k\omega. \tag{5-1}$$

Then, as

$$H = \frac{\partial}{\partial z}(rK) - \mu K$$

and

$$\frac{\partial}{\partial z}(rK) = -\frac{2}{r}\sum_{k=1}^{\infty}(-\eta)^k k\left(\frac{r-z}{\rho}\right)^k \cos k\omega$$

we shall get

$$H = -\frac{\mu}{r} - \frac{2}{r}\sum_{k=1}^{\infty}(-\eta)^k \frac{r-z^k}{\rho}(k+\mu)\cos k\omega. \tag{5-2}$$

If we make $z=0$ and $r=\rho$ in (5-1) and (5-2), we shall have

$$L_1(\omega) = 1 + 2\sum_{k=1}^{\infty}(-\eta)^k \cos k\omega \tag{5-3}$$

and

$$\Omega_2(\omega) = -\mu - 2\sum_{k=1}^{\infty}(-\eta)^k(k+\mu)\cos k\omega. \tag{5-4}$$

These series are absolutely convergent as, in general, $\eta<1$. The case of the magnetic equator, where $\eta=1$, must be considered separately.

VI. COMPUTATION OF THE VERTICAL DERIVATIVES

Our next problem is the computation of the vertical derivatives $g', g'', \cdots$, directly from the recorded anomaly Z or T. It is well known that these derivatives are more convenient for the interpretation, as they more clearly point out the various anomalies, the separating power of the derivatives being greater. We shall see, further, that they are easier to compute, as the convergence of the integrals appearing in the computation is more rapid.

Let us first consider the meaning of the vertical pseudo-gravimetric gradient $g'(x, y)$ (the accent indicates the derivative with respect to z). The fundamental relation (3-1) shows that the vertical component Z is the oblique derivative of g. Let us assume that the geological structure, cause of the anomalies, is in the region of the magnetic pole. Then the vector $\vec{\nu}$ is vertical; the derivative with respect to ν is identical to $\partial g/\partial z$. On the other hand, at the pole, the component Z is identical to T, and, thus

$$\frac{\partial g}{\partial z} = T_{(\text{pole})}.$$

Thus the pseudo-gravimetric vertical gradient g' is nothing else than the *magnetic anomaly reduced to the pole.*

Let us suppose that the whole geological anomaly is carried over to the area of the magnetic pole, or, in other words, let us replace the actual magnetic field, which presents some inclination, by a vertical one. The results of measurements of the total field, performed under such conditions, would precisely give the pseudo-gravimetric vertical gradient.

When computing the vertical derivatives, one must keep in mind that the kernels are no longer continuous at the origin of the coordinates. This singular point, thus, should be isolated by a small circle of radius ϵ, to separate the plane π in two regions: the inside and the outside of this circle. Instead of (3-3), we shall write:

$$g = I_\epsilon(z) + \frac{1}{2\pi}\iint_{\rho>\epsilon} KZdS$$

$I_\epsilon(z)$ being the integral extended to the area $\rho<\epsilon$. The integral (4-3) will be similarly handled.

As to the field Z (or T) in the small circle, it is harmonic, thus analytic, and, accordingly, can be developed into series such as

$$Z = A + B\xi + C\eta + D\xi^2 + \cdots$$

or, in polar coordinates:

$$Z = A + (B\cos\omega + C\sin\omega)\rho + O(\rho^2).$$

We shall use this expression and that (5-1), of K, to compute $I_\epsilon(z)$. Integrating first with respect to ω, we get

$$\frac{1}{2\pi}\int_0^{2\pi} KZd\omega = \frac{A}{r} - \eta B\frac{r-z}{r} + O(\rho^2)$$

Integrating then, with respect to ρ, from 0 to ϵ

$$I_\epsilon(z) = \frac{1}{2\pi}\iint_{\rho>\epsilon} KZ\rho d\rho\cdot d\omega = A(r-z) - \eta B\left(\frac{\epsilon^2}{2} - zr + z^2\right)$$

where

$$r = \sqrt{(z^2+\epsilon^2)}.$$

If we put, now, $z=0$, the value of $I_\epsilon(z)$ is $A\cdot\epsilon+O(\epsilon^2)$. It tends toward zero with ϵ. But, computing the derivatives, for $z=0$, we have

$$I_\epsilon'(0) = -A + \eta B\epsilon + O(\epsilon^2).$$

and

$$I_\epsilon''(0) = \frac{A}{\epsilon} - 2\eta B + O(\epsilon).$$

Thus:

$$g' = -A + \frac{1}{2\pi}\iint_{\rho>\epsilon} K'Z\rho d\rho\cdot d\omega$$

and

$$g'' = \frac{A}{\epsilon} - 2\eta B + \frac{1}{2\pi}\int\int_{\rho>\epsilon} K'' Z \rho d\rho \cdot d\omega.$$

The accents still indicate the derivatives with respect to z. We have the right to differentiate under the integral sign, after eliminating the singular element.

To compute the derivative K', we only need to take the second derivative of u, which we have already computed. We find:

$$u'' = K' = \frac{1}{\rho^2} L_1(\omega) \tag{6-1}$$

with

$$L_2(\omega) = \frac{\lambda(\lambda + \cos\omega)}{(1 + \lambda\cos\omega)^2} = 2\eta\cos\omega - 4\eta^2\cos 2\omega + 6\eta^3\cos 3\omega - \cdots. \tag{6-2}$$

The same method, applied to K, gives

$$K'' = \frac{1}{\rho^2} L_3(\omega) \tag{6-3}$$

with

$$L_3(\omega) = 1 + 6\eta^2\cos 2\omega - 16\eta^3\cos 3\omega + \cdots. \tag{6-4}$$

It is remarkable that the (6-2) series has no constant term. We can thus write the final formula as follows:

$$g' = -Z(0) + \frac{1}{2\pi}\int\int Z(\rho, \omega) L_2(\omega)\frac{d\rho}{\rho} d\omega \tag{6-5}$$

and we know that the integral comprises no singular element.

As for the (6-4) series, the missing term is that in $\cos\omega$. Therefore

$$\frac{1}{2\pi}\int_0^{2\pi} L_3(\omega)\cos\omega d\omega = 0.$$

Let us now consider a constant anomaly, equal to $A = Z(0)$, and compute the integral for the whole area outside of the small circle. We have:

$$\frac{1}{2\pi}\int\int_{\rho>\epsilon} L_3(\omega)\frac{d\rho}{\rho^2} d\omega = -\frac{A}{\epsilon}.$$

This value compensates the identical, but of opposite sign, term in $I''(0)$. Thus the singular element is completely eliminated and we can put $\epsilon = 0$, removing the circle which we excluded at first. We finally obtain the following formula:

$$g'' = -2\eta\left(\frac{\partial Z}{\partial x}\right)_0 + \frac{1}{2\pi}\iint [Z(\rho,\omega) - Z(0)]L_2(\omega)\frac{d\rho}{\rho^2}\,d\omega \qquad (6\text{-}6)$$

for the second pseudo-gravimetric derivative.

The same method will permit to compute the derivatives g', g'', $\cdots$, as functionals of T. It is not necessary to repeat the reasoning; it suffices to observe that, when passing from K to H, the first term of the Fourier's series is multiplied by $-\mu$, the second one by $-(1+\mu)$. Thus the constant A must be replaced by $-\mu A$ and B by $-(1+\mu)B$. The final formulae are as follows:

$$g' = -\mu T(0) - \frac{1}{2\pi}\iint T(\rho,\omega)\Omega_3(\omega)\frac{d\rho}{\rho}\,d\omega \qquad (6\text{-}7)$$

and

$$g'' = -2\lambda\left(\frac{\partial T}{\partial x}\right)_0 - \frac{1}{2\pi}\iint [T(\rho,\omega) - T(0)]\Omega_4(\omega)\frac{d\rho}{\rho^2}\,d\omega \qquad (6\text{-}8)$$

with

$$\Omega_3(\omega) = 2\sum_{k=1}^{\infty}(-\eta)^k k(k+\mu)\cos k\omega \qquad (6\text{-}9)$$

and

$$\Omega_4(\omega) = \mu - 2\sum_{k=1}^{\infty}(-\eta)^k(k^2-1)(k+\mu)\cos k\omega. \qquad (6\text{-}10)$$

The transformations may be just as easily obtained for permitting one to form the derivative g''' directly from Z or T. We shall not elaborate, in order to save space.

VII. PRACTICAL FORMULAE FOR THE COMPUTATION OF THE PSEUDO-GRAVIMETRIC ANOMALIES—INTEGRATION WITH RESPECT TO ω

Expressions such as (4-13), (6-7), (6-8) are the theoretical formulae giving g, g', g'' as functionals of the magnetic anomaly T. Of course, it is necessary to find some simple, accurate and rapid means for the carrying out the practical computation of these expressions.

A very-large number of methods can be imagined. The most convenient seems to be the use of a "canonical grid." It is the method commonly used for the computation of the vertical derivatives. Its main advantage is that it does not entail numerous readings on the map, and lends itself easily to computation, through use of punched card machines. This is a well known method for geophysicists, so we do not need to go into details.

The usual square grid, or a trigonal grid—such as that illustrated in Figure 2—may be used equally. The method is the same, whichever be the data to be computed: g, g' or g''. We shall therefore consider only one of these formulae. For

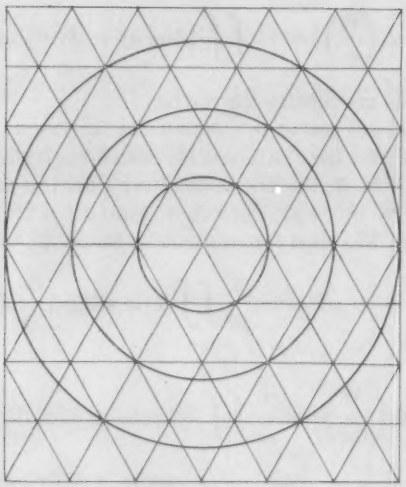

FIG. 2

instance, let us consider the expression (6-7), for the reduction of aeromagnetic anomalies to the pole. It first contains a constant term $-\mu T(o)$ which needs no computation (it is read directly on the map) and a double integral:

$$I = \frac{1}{2\pi} \iint T(\rho, \omega)\Omega_3(\omega) \frac{d\rho}{\rho} d\omega$$

covering the whole plane of measurements.

We shall first integrate with respect to ω, putting

$$\overline{T}(\rho) = \frac{1}{2\pi} \int_0^{2\pi} T(\rho, \omega)\Omega_3(\omega) d\omega. \tag{7-1}$$

Then, we shall integrate with respect to ρ

$$I = \int_0^{\infty} \overline{T}(\rho) \frac{d\rho}{\rho}. \tag{7-2}$$

Note that this is not an absolute requirement. It would be possible, too, to integrate first with respect to ρ, this would require some precautions. In fact, it is the only possible method in the case of an irregular grid, for instance a rectangular or star-shaped one, which is sometimes more advantageous. But, in the case of a trigonal grid (Fig. 2) considered in our example, it is more convenient to integrate first with respect to ω.

The function $\Omega_3(\omega)$ appearing in (7-1) and acting as a weight function can be developed into Fourier's series (6-9). $T(\rho, \omega)$ is an experimental function known

at six canonical points on the circle of fixed radius ρ. The six azimuths are equally spaced; their directions are determined by the angles

$$\omega = \frac{\pi\nu}{3} \quad \text{with} \quad \nu = 0, 1, 2, 3, 4, 5.$$

We shall represent these values read on the grid by the notation $T_\rho(\nu)$. It is obviously a periodic function; it would thus be natural to develop it, too, into a trigonometrical series. However, we propose to take a slightly different approach. Let us put:

$$T(\rho, \omega) = T\rho(0)\psi(\omega) + T\rho(1)\psi\left(\omega - \frac{\pi}{3}\right) + T\rho(2)\psi\left(\omega - \frac{2\pi}{3}\right) + \cdots + T\rho(5)\psi\left(\omega - \frac{5\pi}{3}\right).$$

$\psi(\omega)$ is an influence function of the point of zero azimuth, such azimuth being directed toward the magnetic North. For $\omega = 0$, its value is 1; it is zero in any other point. These conditions are satisfied for an infinite number of functions. To make a choice, we shall introduce a "simplicity condition." Like the anonaly T, the influence function must present as few higher harmonics as possible. This condi-

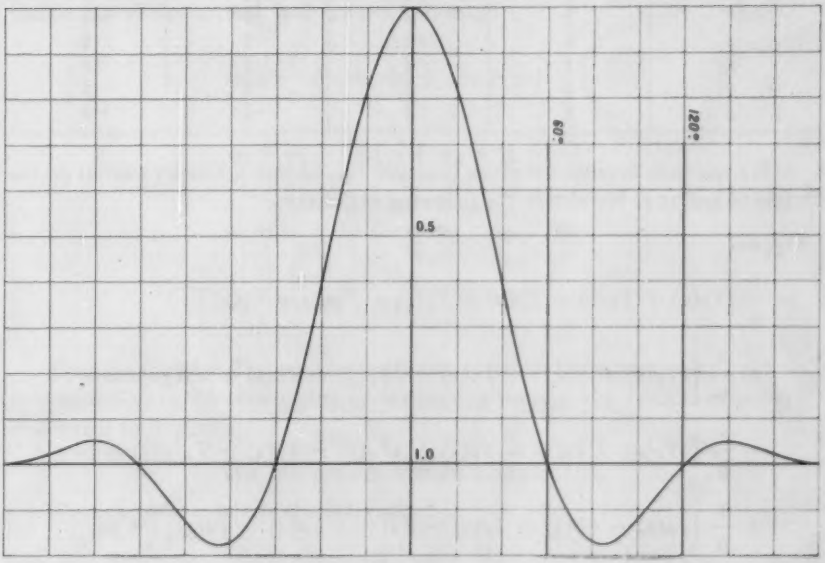

FIG. 3

tion, obviously, is in accordance with the filtering qualities of the canonical grid. We shall thus put:

$$\psi(\omega) = \frac{1}{6}(1 + \cos\omega)(2\cos\omega - 1)(2\cos\omega + 1)$$
$$= \frac{1}{6} + \frac{1}{3}\cos\omega + \frac{1}{3}\cos 2\omega + \frac{1}{6}\cos 3\omega \tag{7-3}$$

because this function is equal to zero for $\cos\omega = -1$, $+\frac{1}{2}$ and $-\frac{1}{2}$, while for $\omega = 0$, it has the value $\psi(0) = 1$. This is the simplest influence function satisfying to the foresaid conditions indicated above. Figure 3 shows the pattern of this function.

As to the other azimuths, we shall compute:

$$\psi\left(\omega - \frac{\nu\pi}{3}\right) = \frac{1}{6} + \frac{1}{3}\cos\frac{\nu\pi}{3}\cos\omega + \frac{1}{3}\cos\frac{2\nu\pi}{3}\cos 2\omega + \frac{1}{6}\cos\nu\pi\cos 3\omega$$
$$+ \text{ the odd terms in } \sin\omega, \sin 2\omega, \sin 3\omega$$

(we do not need to express these odd terms, as the function Ω_3 is an even one).

The Fourier's coefficients of these functions are tabulated hereafter:

ν	1	$\cos\omega$	$\cos 2\omega$	$\cos 3\omega$
0	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{6}$
1	$\frac{1}{6}$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{6}$
2	$\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$
3	$\frac{1}{6}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{6}$
4	$\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$
5	$\frac{1}{6}$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{6}$

We can now develop the given function $T(\rho, \omega)$ into a Fourier's series on the circle of radius ρ. We obtain the following expression

$$T(\rho, \omega)$$
$$= \frac{1}{6}[T\rho(0) + T\rho(1) + T\rho(2) + T\rho(3) + T\rho(4) + T\rho(5)]$$
$$+ \frac{1}{6}[2T\rho(0) + T\rho(1) - T\rho(2) - 2T\rho(3) - T\rho(4) + T\rho(5)]\cos\omega$$
$$+ \frac{1}{6}[2T\rho(0) - T\rho(1) - T\rho(2) + 2T\rho(3) - T\rho(4) - T\rho(5)]\cos 2\omega \tag{7-4}$$
$$+ \frac{1}{6}[T\rho(0) - T\rho(1) + T\rho(2) - T\rho(3) + T\rho(4) - T\rho(5)]\cos 3\omega$$
$$+ \text{ odd terms}$$

(it is useless to write these odd terms, since they disappear when integrating with respect to ω).

To compute the integral (7-1), we have to integrate the product of two functions T and Ω_3, given by their developments of the Fourier's series (5-9) and (7-4). To be more general, let us write the development of the weight function as follows:

$$\Omega(\omega) = \gamma_0 + 2\gamma_1 \cos \omega + 2\gamma_2 \cos 2\omega + \cdots.$$

For the function Ω_3, the values of the coefficients are:

$$\gamma_0 = 0, \qquad \gamma_1 = -\eta(1 + \mu)$$
$$\gamma_2 = 2\eta^2(2 + \mu)$$
$$\gamma_3 = -3\eta^3(3 + \mu)$$
$$\cdots\cdots\cdots$$

For the integration, we only need to sum up the products of the coefficients of (7-4) by the γs. We obtain an expression which can be conveniently rearranged according to the canonical values of the anomaly:

$$\overline{T}(\rho) = \alpha_0 T\rho(0) + \alpha_1 T\rho(1) + \cdots + \alpha_6 T\rho(5) \tag{7-5}$$

in order to show the numerical coefficients by which the readings from the grid must be multiplied. The expressions of these coefficients which depend on the inclination of the normal field are the following:

$$\alpha_0 = \frac{1}{6}(\gamma_0 + 2\gamma_1 + 2\gamma_2 + \gamma_3)$$

$$\alpha_1 = \alpha_5 = \frac{1}{6}(\gamma_0 + \gamma_1 - \gamma_2 - \gamma_3)$$

$$\alpha_2 = \alpha_4 = \frac{1}{6}(\gamma_0 - \gamma_1 - \gamma_2 + \gamma_3)$$

$$\alpha_3 = \frac{1}{6}(\gamma_0 + 2\gamma_1 + 2\gamma_2 - \gamma_3)$$

Thus the function $\overline{T}(\rho)$ may be easily computed for the values $\rho = 1, 2, 3, \cdots$, corresponding to the radii of the circles passing through the vertices of the grid illustrated on Figure 2.

VIII. INTEGRATION WITH RESPECT TO ρ

We must now compute the integral

$$I = \int_0^\infty \overline{T}(\rho)\,\frac{d\rho}{\rho} \tag{8-1}$$

where the function $\overline{T}(\rho)$, equal to zero at the origin, is known at points of abscissae $\rho = 1, 2, 3, \cdots$. Numerous methods are available to effect the approximate quadratures. We shall outline here a method which, while perhaps not the most accurate, is very widely known, and the easiest to describe. The axis $O\rho$ will be divided into partial intervals:

$$(0, 1) - (1, 3) - (3, 5) \quad \text{and} \quad (5, \infty).$$

We shall admit that, in the first interval $(0, 1)$, the function $\overline{T}(\rho)/\rho$ may be represented by a parabola

$$\frac{\overline{T}(\rho)}{\rho} = A + B\rho + C\rho^2$$

passing through the points $\rho = 1$, 2 and 3. We shall have:

$$A + \frac{1}{2}B + \frac{1}{3}C = \int_0^\infty \frac{\overline{T}}{\rho}\, d\rho$$

$$A + B + C = \overline{T}_1$$

$$A + 2B + 4C = \frac{1}{2}\overline{T}_2$$

$$A + 3B + 9C = \frac{1}{3}\overline{T}_3$$

where $\overline{T}_k = \overline{T}(k)$. Eliminating A, B, and C from these four equations, we get:

$$\int_0^1 \frac{T(\rho)}{\rho}\, d\rho = 2\overline{T}_1 - \frac{3}{4}\overline{T}_2 + \frac{1}{6}\overline{T}_3. \tag{8-2}$$

For the intervals $(1, 3)$ and $(3, 5)$, we shall apply Simpson's rule, which causes us to put:

$$\int_1^3 \overline{T}(\rho)\frac{d\rho}{\rho} = \frac{1}{3}\overline{T}_1 + \frac{1}{3}\overline{T}_2 + \frac{1}{9}\overline{T}_3 \tag{8-3}$$

$$\int_3^5 \overline{T}(\rho)\frac{d\rho}{\rho} = \frac{1}{9}\overline{T}_3 + \frac{2}{3}\overline{T}_4 + \frac{1}{15}\overline{T}_5. \tag{8-4}$$

Finally, the last interval $(5, \infty)$ corresponds to the "tail" of the curve $\overline{T}(\rho)$, where the function can be approximately expressed using the following formula:

$$\overline{T} = \frac{A}{\rho^2} + \frac{B}{\rho^3}.$$

In fact, the average weighted T anomaly decreases like the square or the cube of the distance. To compute the constants A and B we shall take into considera-

tion the fact that the curve passes through the points $\rho=4$ and $\rho=5$. We shall then get three equations:

$$\frac{A}{50}+\frac{B}{375}=\int_5^\infty \overline{T}(\rho)\,\frac{d\rho}{\rho}$$

$$\frac{A}{16}+\frac{B}{64}=\overline{T}_4$$

$$\frac{A}{25}+\frac{B}{125}=\overline{T}_5$$

whence, eliminating A and B:

$$\int_5^\infty \overline{T}(\rho)\,\frac{d\rho}{\rho}=-\frac{32}{75}\,\overline{T}_4+\frac{7}{6}\,\overline{T}_5. \tag{8-5}$$

Summing the expressions (8-2), (8-3), (8-4) and (8-5), we get

$$\int_0^\infty \overline{T}(\rho)\,\frac{d\rho}{\rho}=\frac{7}{3}\,\overline{T}_1-\frac{1}{12}\,\overline{T}_2+\frac{7}{18}\,\overline{T}_3-\frac{7}{75}\,\overline{T}_4+\frac{37}{30}\,\overline{T}_5.$$

To check this formula, we chose a theoretical function

$$\overline{T}=\frac{a^2\rho}{(\rho^2+a^2)^{3/2}}. \tag{8-6}$$

The exact value of the integral is equal to unity.

The approximate values, computed with the (8-6) formula are shown in the table below:

a	I	Error
2	1.0906	9.1%
3	1.0227	2.3%
4	0.9950	−0.5%

For a small value of the constant a, the curve $\overline{T}$ is very sharp at the origin. With increasing a, the error rapidly decreases.

The integration may be made more accurate, through separate consideration of an additional partial interval (5, 7).

In any case, the result of the integration with respect to ρ is represented by a linear expression

$$\int_0^\infty \overline{T}(\rho)\,\frac{d\rho}{\rho}=\sum_{(k)}\beta_k\overline{T}_k \tag{8-7}$$

where the β_k are the numerical coefficients computed once for all. This formula should be combined with (7-5) to give the final result:

$$I = \sum_{\nu \cdot k} \alpha_\nu \beta_k T_k(\gamma). \tag{8-8}$$

Finally, we must not forget to add the constant term $-\mu T_0$ appearing in (6-7).

Figure 4 shows the values of the coefficients at their respective locations.

The process just described is well suited for dips $I > 30°$ of the normal magnetic field. For smaller dips, near the magnetic equator, the computation requires more care. In all cases, the computation practically involves the reading of the values of the field T on a canonical grid, followed by a cumulative multiplication

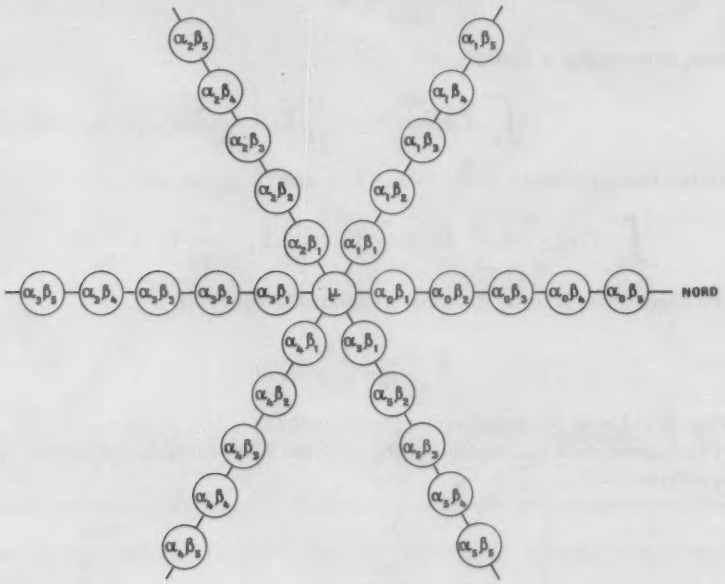

FIG. 4

of the readings by numerical coefficients computed once for all, and which depends only upon the mean average geomagnetic latitude of the area under consideration.

Of course, this computation is time consuming, if one uses ordinary computers. However, it can be considerably speeded up with the use of electronic computers operating with punched cards. The values of the field, read on a point of the canonical grid, and the coordinates of this point (oblique if the grid is trigonal) are plotted on "mark sensing" cards (one card for each point), transformed into normal cards by the reproducer.

A first list is then given by the tabulator, a list that is compared to the readings. This operation is designed to simultaneously check the readings, the plottings and the punching. The computation itself is carried out in the computer.

Finally, the cards pass again through the tabulator, which prepares the final list of the values of the transformed field.

Figure 5 gives an example of a grid with the numerical coefficients for the reduction to the pole of the field T in an area where the average dip is 60°.

FORMULA AND COEFFICIENTS TO COMPUTE THE PSEUDO-
-GRAVIMETRIC VERTICAL GRADIENT

$$-g' = -\sin I \cdot T_0 + \frac{1}{2\pi} \iint T(\rho,\omega) \cdot \Omega_3(\omega) \frac{d\rho}{\rho} d\omega$$

$$\Omega_3 = \sin I \frac{3\cos I + \cos I(2+\cos^2 I)\cos\omega}{(1+\cos I \cdot \cos\omega)^3}$$

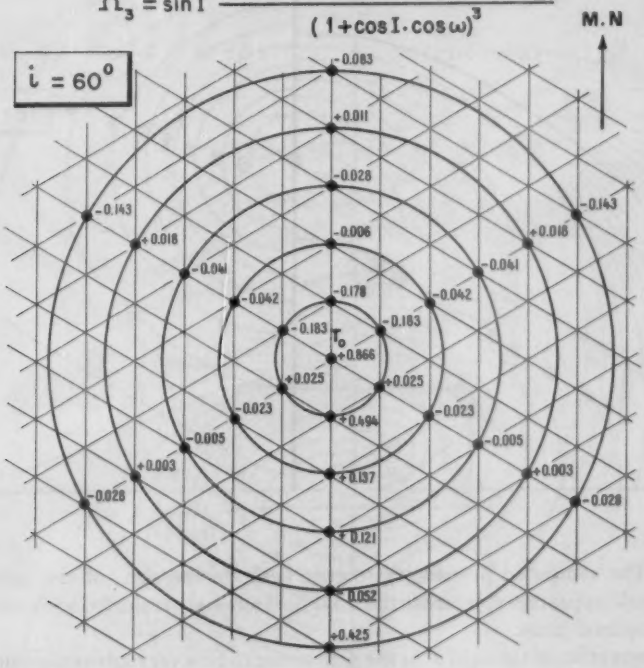

FIG. 5

Figure 6 shows the anomaly caused by a sphere buried at a depth h, shown on the map. On the left the contours of the total field anomaly are plotted. On the right side, the field of the computed pseudo-gravimetric vertical gradient is represented. The computed curves are almost perfect circles, and their common center on the apex above the sphere. The two external curves are very slightly affected by the unavoidable errors of the numerical computation.

Figure 7 shows the effect of a vertical prismatic body, of rectangular cross

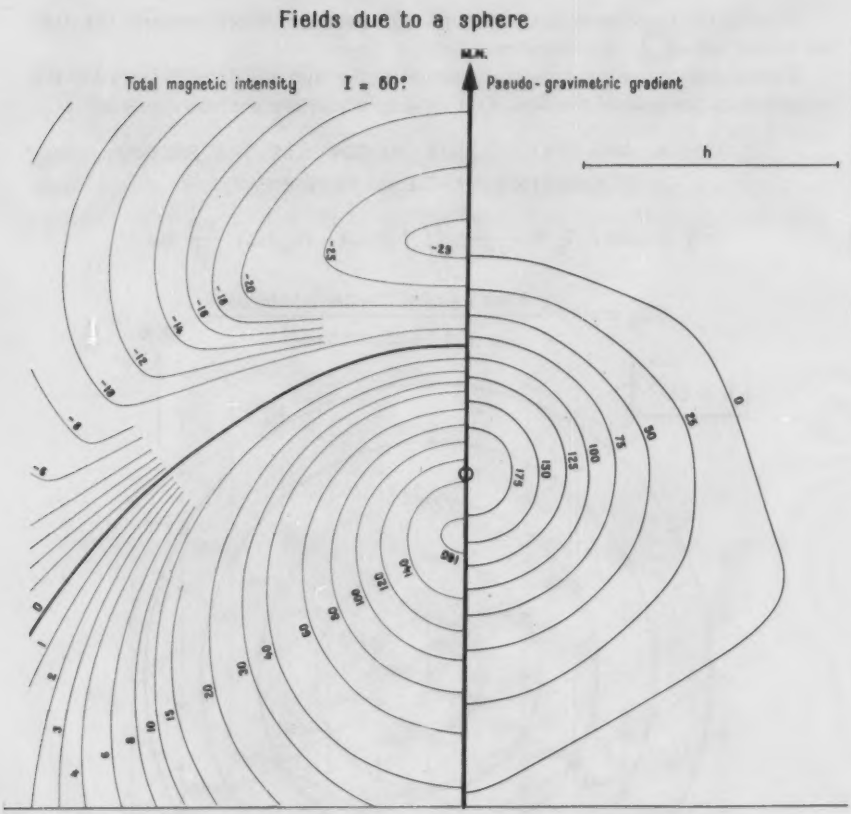

FIG. 6

section. The computed psuedo-gravimetric field, on the right of the figure, has a symmetric appearance, whereas the total field anomaly is shifted with respect to the magnetized mass.

The reduction of the field T to the pole seems to be a very advantageous transformation for the following reasons:

1) the qualitative interpretation of the transformed map is easier and more immediate, as the anomalies are not shifted as a result of the obliquity of the normal field;
2) the comparison of the results of a survey with a geological map is much easier. One does not need to take into consideration the shifting of the magnetic anomalies;
3) the transformed map can be compared to a gravimetric map, much better

than the original aeromagnetic map, especially if this latter too is transformed into a map of the first vertical derivatives. Indeed, the two quantities, then, are of the same nature;

4) the pseudo-gravimetric anomalies do not depend upon the inclination of the normal field, nor on the orientation of the tectonic structure. This simplifies the quantitative interpretation and the evaluation of depths. The number of typical cases, such as blocks, faults and so on, is consider-

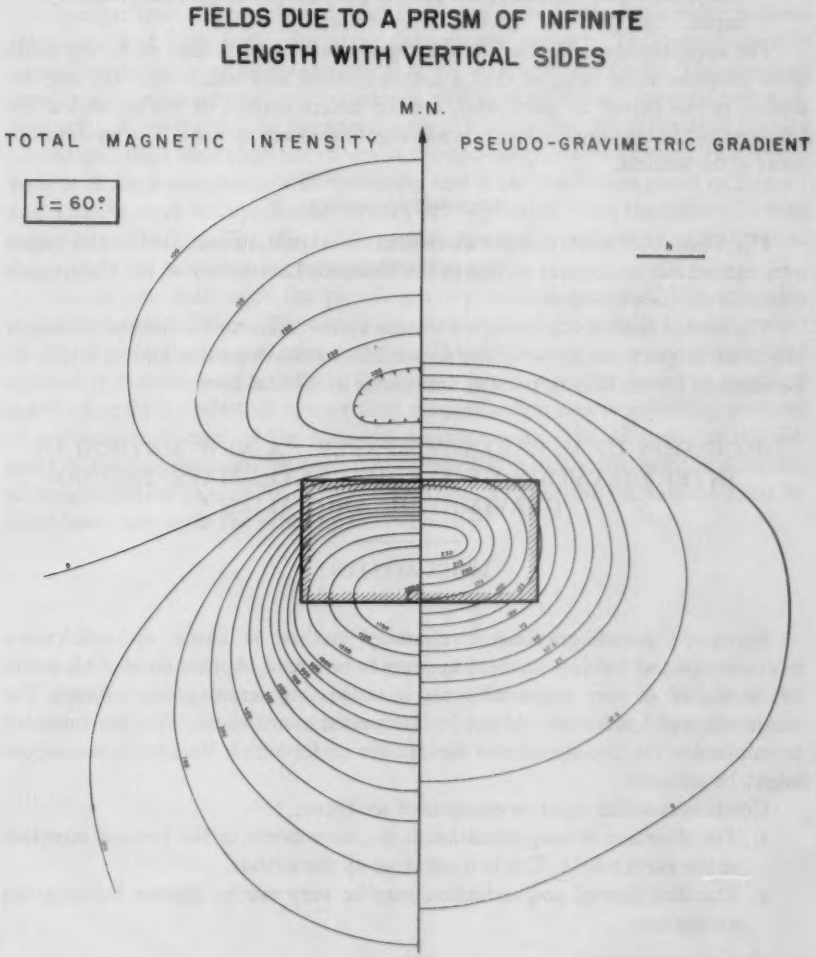

FIG. 7

ably reduced. Once computed, a single typical anomaly can be used for all dips and orientations;

5) the computation of the theoretical pseudo-gravimetric anomalies is simpler than that of the magnetic anomalies. For instance, let us consider a vertical block. In magnetism, the vertical walls of the compartment give rise to a very complex anomaly, which is eliminated if the structure is located at the pole. It is easy to draw a number of simple nomographs with which the computation of the pseudo-gravimetric anomalies becomes very rapid.

The approximate computation of integrals such as (6-7) and (6-8) has made some progress since 1955, so that a better method now exists than the one described in the paper. In particular, for the determination of the numerical coefficients of the transformation, it is no longer necessary to use a Fourier development of the kernels.

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The theoretical work and the numerical computations recorded in this paper were carried out on account of, and in the Research Laboratory of, the Compagnie Générale de Geophysique.

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DISCUSSION OF V. BARANOV'S PAPER, "A NEW METHOD OF INTERPRETATION OF AEROMAGNETIC MAPS, PSEUDO-GRAVIMETRIC ANOMALIES"*

JAMES AFFLECK†

Baranov's pseudo-gravimetric anomaly method is based on well-known relationships and his development appears to be sound. Applications of his methods should be of very appreciable use in evaluating aeromagnetic surveys. The comments which follow should not be interpreted as criticisms. They are intended to emphasize the conditions and limitations under which Baranov's techniques might be utilized.

Conditions which must be recognized are these:

1. The direction of magnetization is not necessarily in the present direction of the earth's field. This is recognized by the author.
2. The direction of magnetization may be very much different for adjacent anomalies.

* Received by the Editor October 18, 1956.

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3. Magnetizations may be non-uniform within a rock mass. Gradational magnetizations seem to be common.

When the three items above are considered, it is obvious that the pseudo-gravity anomaly peaks will not necessarily be coincident with the apex or center of the magnetized mass. Lack of uniformity is undoubtedly more common in magnetizations than in densities.

The author does not imply that his methods can be used quantitatively in conjunction with observed gravity over any area. It is likely that such quantitative comparisons will be inferred, and they may be of appreciable value in some instances. But here again the same dangers are present. The pseudo-gravity anomalies certainly represent the effects of the magnetic rocks only. The observed gravity anomalies represent the combined effects of all rocks, magnetic and non-magnetic. A subtraction of the pseudo-gravity anomalies from the true gravity anomalies might then yield the effects of the non-magnetic rocks only. This would be true if the assumptions held rigorously and if the conditions listed in Items 1 and 3 above were not applicable. If they are applicable, then the difference map might be misleading. The effects of angularity and non-uniformity of magnetizations might be mistaken for sedimentary structure.

The author deals with the pseudo-gravity vertical gradient. His definition might be reworded thus: The pseudo-gravity vertical gradient is the equivalent of what the vertical magnetic intensity would be if the rock mass were magnetized vertically. If considered strictly in this sense, then it would be useful in eliminating the angularity effect of non-vertical magnetization and non-vertical position of the sensing element of the airborne magnetometer. The direction of the element of the magnetometer is probably sufficiently well known, but the direction of magnetization cannot be generally assumed, so that the limitations must be considered here as in the case of pseudo-gravity.

GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 384-397, 9 FIGS.

POLAR MOVEMENT AS INDICATED BY ROCK MAGNETISM*

LYNN G. HOWELL† AND JOSEPH D. MARTINEZ†

ABSTRACT

Measurements of remanent magnetism have been carried out by geophysicists both in this country and in the British Isles in a broad sampling of Paleozoic sediments. The direction of magnetization of these rocks indicates that the positions of the earth's magnetic poles were quite different in Paleozoic times from their positions today. Since it is felt that the magnetic poles are closely tied in with the spin axis of the earth, the locations of the magnetic poles, as averaged over space and time, should indicate the locations of the geographic poles. Determinations of magnetization of Mississippian concretions and other sediments of chemical origin in the Llano uplift area of Texas were made in our laboratory, and indicate pole positions in Carboniferous times consistent with observations made by Blythe in England and by Runcorn in Arizona. Cambrian pole locations, as found from samples in the same area, are included and compared with positions from other work. A few interesting data are shown from the Sawatch formation of Cambrian Age in Colorado.

INTRODUCTION

Polar movement has been discussed in geologic literature for many years in an attempt to explain evidence of climatic changes on a world-wide basis in the distant past. Wegener has even gone so far as to postulate relative movement or drift between the continents. One of the more modern tools in the study of paleoclimates is the oxygen-isotope-ratio method developed by Urey (1948) and his colleagues. There is, however, a limitation here in that only sea water temperatures are considered. It is now beginning to appear that the most direct approach to the determination of the positions of the poles in the past is offered by measurements of the direction of remanent magnetism of rocks of various ages. Already a quantity of data has been accumulated from both igneous and sedimentary formations.

In the case of igneous rocks, it has been demonstrated by various observers that the rock becomes magnetized in the direction of the earth's field as it cools from the molten state through the Curie point. Hospers (1955), on the basis of his own work and the work of others, has concluded that the magnetic pole has remained at or very near the present geographic pole for at least back into the Miocene. It is assumed in all of this work that if averages of the direction of magnetization of samples covering sufficient geologic time (say thousands of years) are taken, the deviations due to secular variation of the magnetic field are reduced so that the position of the earth's magnetic pole agrees with that of the rotational or geographic pole. Thus, Hospers concludes that the geographic poles have not moved appreciably since the end of the Eocene. The close relationship between the magnetic and the geographic poles is not surprising on the basis

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of the modern dynamo theories of earth magnetism of Elsasser (1946 and 1947) and Bullard (1949).

Another interesting observation made on the measurements of igneous rocks is that about half of the Cenozoic lava flows (*Handbuch der Physik*, 1956) show a magnetization in a direction reverse to the usual direction. These data have brought about an argument as to whether or not the magnetic poles of the earth can reverse. There is evidence, as pointed out by Nagata (1952), that some igneous rocks can actually be magnetized in a direction opposite to that of the field applied as they cool from the paramagnetic state. Also, there is other evidence that the field of the earth itself has reversed. Although a mass of data has already been accumulated, this question needs and will undoubtedly receive further study.

In the case of sediments, which in general can be more accurately dated than igneous formations, Runcorn (1955a) and his group at Cambridge as well as others have found very striking evidence that the poles have moved, and in particular that the Paleozoic pole locations are quite different from their present locations. Graham (1949) at the Department of Terrestrial Magnetism in Washington set forth basic criteria for determining the stability of remanent magnetism with respect to geologic time. These criteria were concerned with sedimentary rocks, but the stability question must be applied to both igneous and sedimentary rocks since it is vital to know whether a rock was magnetized at the beginning of its history or later. Graham found that the directions of magnetization in a Silurian formation, folded near the end of the Paleozoic, were quite scattered, but that the directions were brought into good agreement by flattening the fold with the corresponding rotation of the magnetic vectors in space. Graham concluded that the magnetization had been stable at least since the folding at the end of the Paleozoic. The other important finding was that the direction of magnetization was quite different from the direction of the earth's present magnetic field. These data will be referred to later.

Although the manner in which igneous rocks are magnetized is fairly well accepted, the mechanism is not always clear in the case of sedimentary rocks. At times it has been suggested that detrital particles align themselves in the earth's field as they settle in the water, or as they rest in the ooze on the bottom. However, this brings up the question as to whether the particles realign themselves upon striking the bottom, with a resulting change in dip direction of the magnetization. We have recently published some results (Martinez and Howell, 1955b) obtained with chemical sediments for which it would be expected that the magnetization took place during the chemical deposition. This should avoid a possible difficulty encountered with detrital particles.

OBSERVATIONS IN THE LLANO UPLIFT AREA

We have sampled the Barnett formation of Mississippian age in the Llano uplift area of central Texas, the locations being represented by squares in Figure

1. We feel that we have obtained a satisfactory sampling in both time and space as the extreme sample locations are roughly 70 miles apart. The samples were obtained largely from ellipsoidal calcareous concretions, as well as from limestone and shale beds. Figure 2 is a picture of a typical Barnett concretion.

Figure 3 shows a Schmidt projection of the directions of magnetization obtained from individual plugs from the nine locations. The plots show the direction of the north-seeking vector on a lower hemisphere; i.e., all vectors are directed down. The azimuth from north is shown in the conventional manner while the angle made with the vertical is shown as a function of the radius. Thus, a number of the vectors are nearly horizontal in a southeasterly direction. It is very interesting that location *J* reveals a magnetization reversed from that of most of the data. Also several points from locations *D*, *G*, and *H* fall near the direction of the earth's present field, and thus indicate recent magnetization. Some of the other points indicate varying amounts of remagnetization, especially from data taken from some of the shale at location *F*. It is for this reason that the two representative vectors are selected as shown by the two large circles. It is felt that the large cluster of points at the extreme southeast represents a more stable direction of magnetization than vectors closer to the earth's present magnetic field.

FIG. 1. Map showing sample locations in the Llano uplift area of Central Texas.

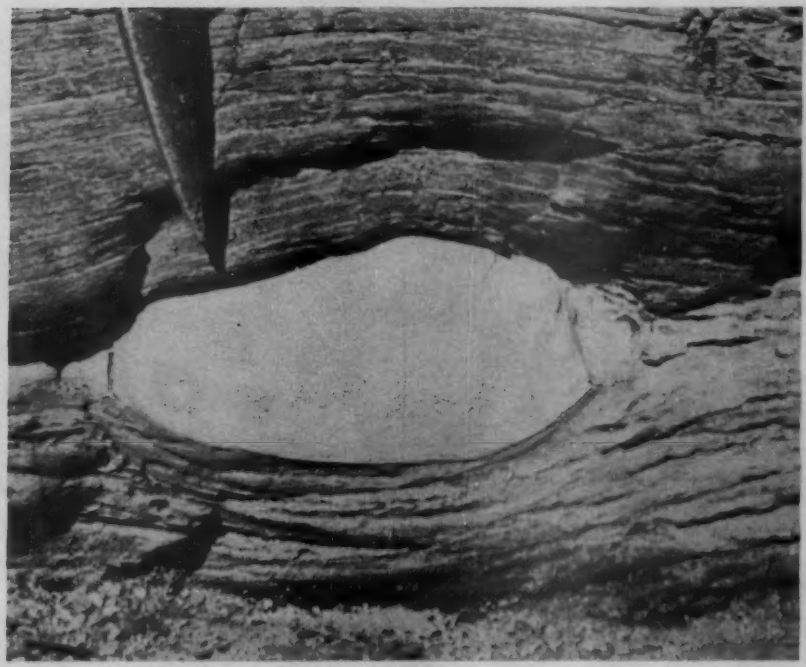

FIG. 2. Typical concretion in Barnett formation of Mississippian age. The point of a geologist's hammer is shown for scale.

LOCATIONS OF THE MAGNETIC POLES

Figure 4 shows the world-wide location of the poles computed from these directions. The computations are made on the usual assumption of a centered-dipole geomagnetic field. The "starred" circles represent the positions of the poles computed from the vector to the southeast, while the plain circles show the positions from the reverse vector. The positions are given below.

	South Pole	North Pole
"Starred" Poles	Lat. 41° N Long. 128° E	Lat. 41° S Long. 52° W
Location *J* Poles	Lat. 43° S Long. 38° W	Lat. 43° N Long. 142° E

The "starred" locations are fairly close to those published as computed from a vector-sum average, from which some of the points were excluded. The "J" poles are the same as previously. As to the map, it is of interest that our pole locations agree quite well with those of Belshe (Runcorn, 1955b) as indicated, his samples coming from Carboniferous rocks in England. The sample location in each case is indicated by the symbol enclosing an "L." Agreement is shown with Runcorn's (1955b) poles from data of Pennsylvanian rocks obtained in the Arizona area. We

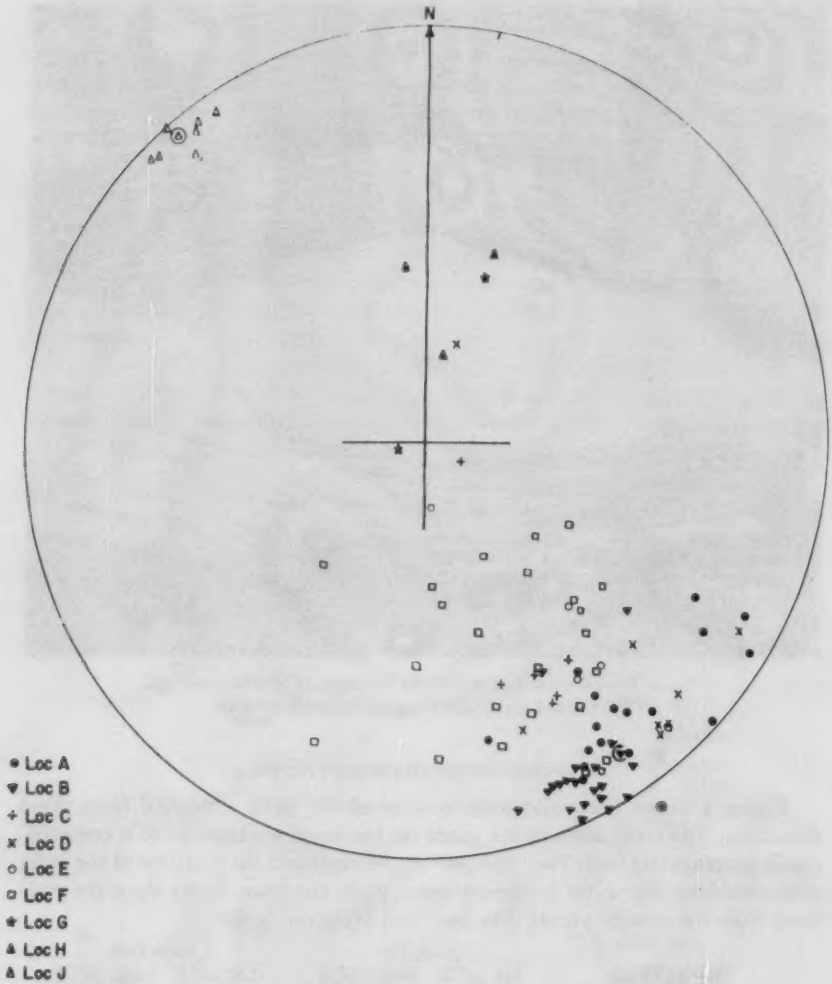

FIG. 3. Barnett magnetic vectors plotted on lower hemisphere of Schmidt net.

feel that this agreement is sufficient evidence that very little continental drift between England and our continent has occurred. It might be pointed out that recently Runcorn (1956) postulated a drift of about 20 degrees mainly on the basis of Paleozoic data. Another point of interest on the map is the equator corresponding to our "starred" poles. This equator passes very close to the areas of Carboniferous and Permian reefs in Texas and New Mexico; thus, the reefs

FIG. 4. Map of Carboniferous poles and equator. Sample locations are indicated by symbols enclosing "*L*."

probably enjoyed a favorable environment of sunlight and warm water at the time they were formed.

FURTHER OBSERVATIONS IN THE LLANO UPLIFT AREA

We have also made measurements on upper Cambrian samples obtained from the Point Peak member of the Wilberns formation in the Llano uplift area. These locations are represented by triangles in Figure 1. The samples in general are siltstone. Figure 5 shows a plot of the magnetic vector directions on a Schmidt net. The few points falling on the upper hemisphere are dotted in. Also, it may

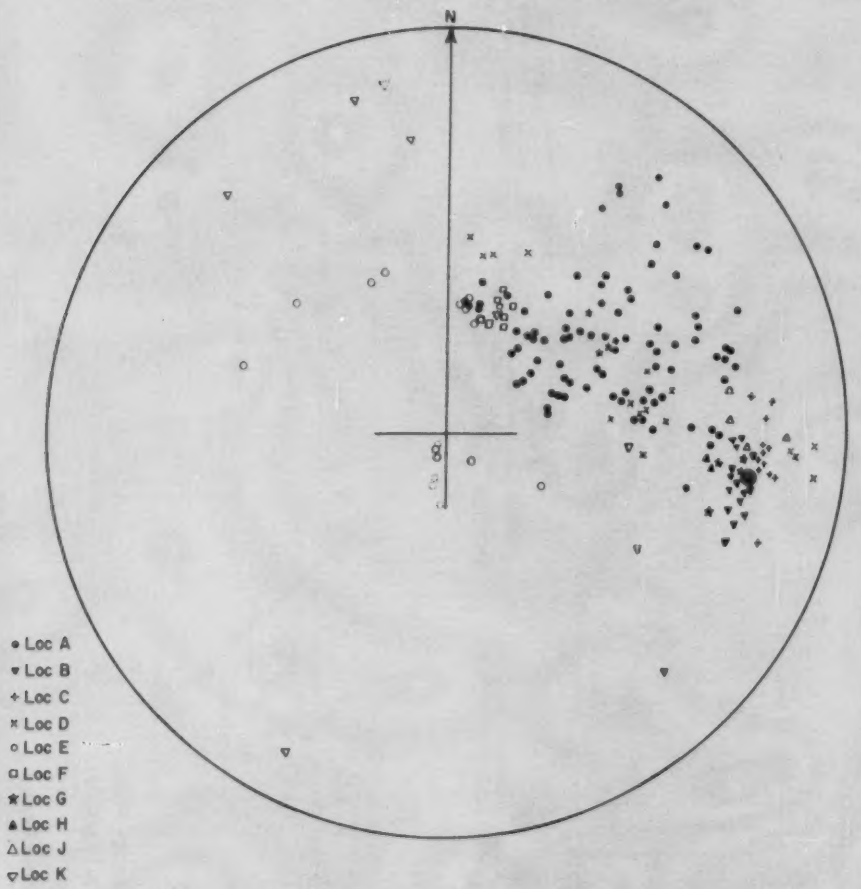

FIG. 5. Point Peak (Cambrian) magnetic vectors, plotted on Schmidt net, all points being on lower hemisphere with exception of dotted points on upper hemisphere.

be mentioned that in general the coordinate system is tied in with the plane of the bed; i.e., stratum dips have been removed. Steep dips occurred at only one location, *K*, and here they ranged from 30 degrees to 60 degrees. The vectors are erratic for this location. On the whole, the Point Peak samples do not exhibit the same magnetic stability as the Barnett. However, a representative vector has been chosen near the head of the points and marked with a multiple circle.

LOCATIONS OF THE MAGNETIC POLES

The pole locations computed from this vector are shown in Figure 6. The positions are given below.

South Pole	North Pole
Lat. 0° Long. 158° E	Lat. 0° Long. 22° W

These pole locations, designated by gray triangles, are in fairly good agreement with those made by Creer (Day and Runcorn, 1955) from samples in Great Britain. The locations by Day and Runcorn (1955) from Arizona samples are in lesser agreement. We have, however, seen no data published for this case. The pole positions obtained by Du Bois (1955) from the upper Keweenawan in Michigan are included, although the Keweenawan is generally classified as pre-Cambrian. There has, however, been some question concerning the age of the upper Keweenawan in Michigan. The magnetic data indicate the possibility that it is of Cambrian age, or at least very near Cambrian, as pointed out by Du Bois.

We have also included our pole locations (squares) from the Sawatch formation in Colorado. The vector data are shown on the Schmidt plot in Figure 7. Although we do not have widespread data from this formation, having sampled only two locations, the data suggest the interesting possibility that this Cambrian rock may have been magnetized near the end of Paleozoic time. The rocks were determined, on the basis of thin section examination, to be principally sandy dolomites containing abundant glauconite. Much hematite is present and occurs in irregular masses, interstitial filling between dolomite crystals, a fine dust incorporated in the lattice of the dolomite crystals, and as a partial replacement of glauconite and in some cases quartz. The glauconite, except as noted above, is unaltered. The hematite seems to have formed concurrently with dolomitization.

One possible mechanism for late postdepositional magnetization might be formation and magnetization of the hematite in a late dolomitization. Another possible mechanism might be remagnetization of the rock in the presence of stresses related to formation of the Ancestral Rockies.

Figure 8 shows the pole data obtained from Triassic-Permian formations by various observers. In the bottom part of the map there are shown pole positions computed by Graham (1955) from data for individual sample locations made by Clegg, Almond and Stubbs (1954) at London University. The locations are in Triassic outcrops in England. Also shown are poles for the individual locations made by Graham (1955) on Triassic-Permian outcrops in Maryland and in the

FIG. 6. Map of Cambrian pole locations.

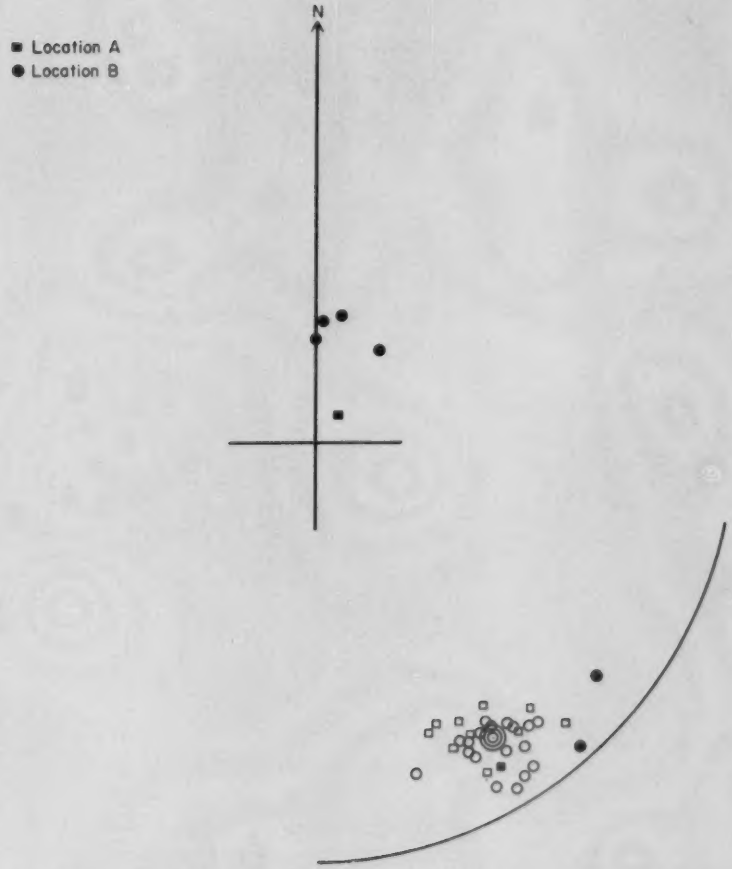

FIG. 7. Sawatch magnetic vectors plotted on Schmidt net. Solid symbols represent lower hemisphere points; open symbols, upper hemisphere.

Arizona-New Mexico area. These poles are in some instances North and in others, South. From the estimated mean positions of the poles, as shown in the upper left hand corner of Figure 8, the agreement in the positions of the poles is very good between data from England and from the United States. The Triassic pole located by Creer (Day and Runcorn, 1955) represents another determination using the same measurements of Clegg as given above. The Triassic and Permian poles located by Runcorn (1955b) from measurements on rocks obtained in the Utah-Arizona area are in fair agreement. Doell (1955) also obtained data from the same Permian formation in Arizona as sampled by Runcorn. The pole loca-

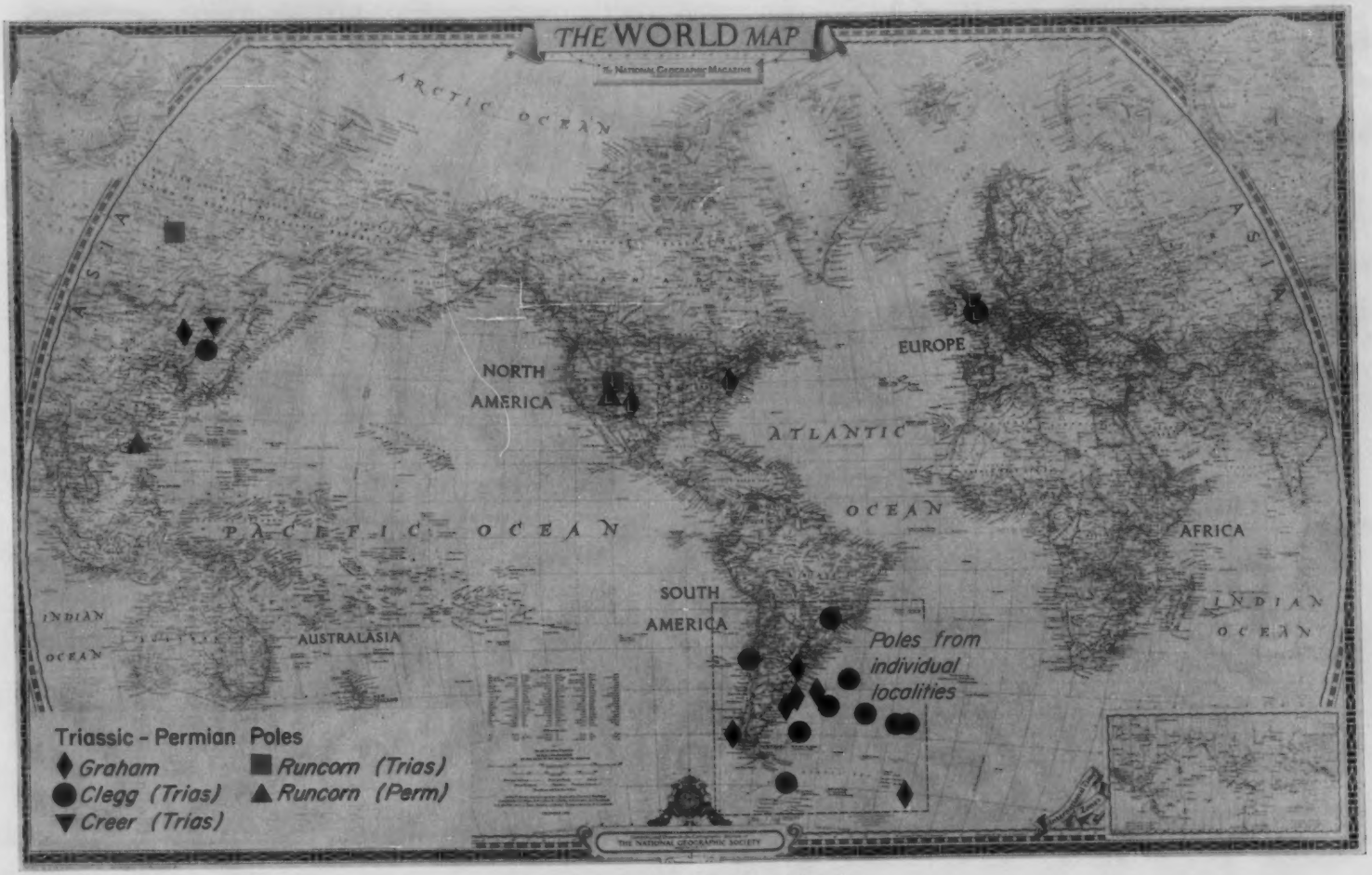

FIG. 8. Map of Triassic-Permian pole locations.

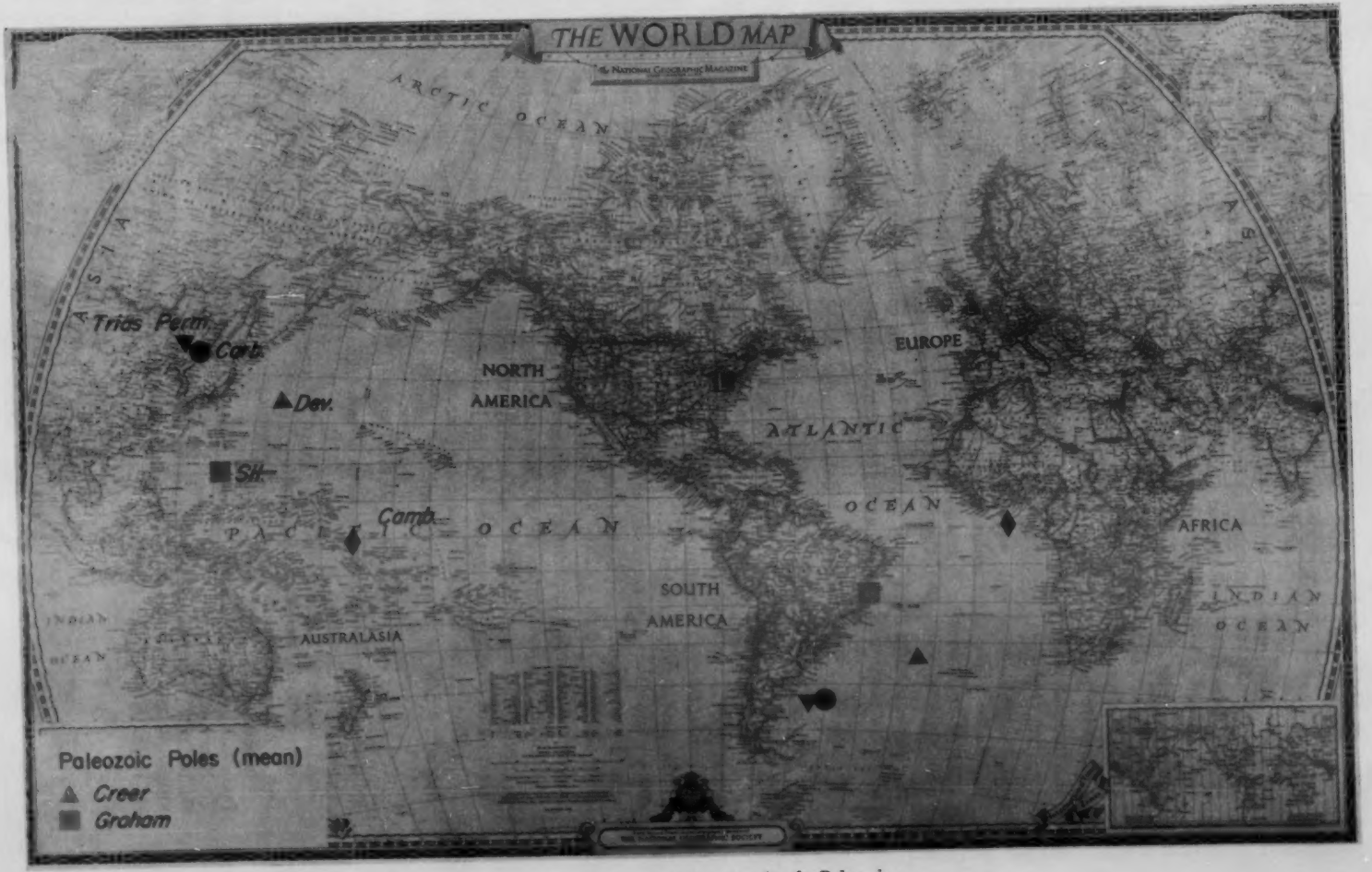

FIG. 9. Map of mean pole locations for the Paleozoic.

tion in the northern hemisphere as determined by Doell is somewhat to the north of that determined by Runcorn.

In Figure 9 approximate averages are shown for the positions of the poles in Paleozoic times (the Triassic being lumped in with the Permian). In obtaining a mean for the Cambrian poles, only the determinations by Runcorn, by Creer, and by us, using the Point Peak data, are considered. Two other ages, not shown before, are included. These are the pole locations from Graham's 1949 data for the folded Silurian at Pinto, Maryland, and the Devonian pole locations made by Creer (Runcorn, 1955b) from British samples. It should be remembered that all of these paleozoic data were obtained from sedimentary formations.

On the whole, there seems to be a suggestion that the poles moved in a progressive fashion during Paleozoic time; certainly their positions are quite different from those of today. Over-all, there is fairly good agreement between the pole locations obtained from Great Britain and from our country with the possibility of only a small displacement as suggested by Runcorn.

CONCLUSIONS

In conclusion, the geophysicists now have a powerful tool for studying changes which not only affect paleoclimates but also may produce crustal shear patterns on a world-wide basis as postulated by Vening-Meinesz (1947). We who are engaged in geophysical prospecting are beginning to realize more and more the importance of the remanent magnetism of igneous rocks in magnetic surveys. In the past, induced magnetism has received the major portion of the emphasis, but we know that in some cases the remanent magnetism of an igneous rock may exceed the amount of induced magnetization by one-hundred fold. Also, with more and more paleomagnetic data the diagnostic properties of remanent magnetism are becoming apparent. As an example, Lundbak (1956) in Denmark has pointed out the possibilities of analyzing paleomagnetic data from a combination of gravity and magnetic surveys. Certainly it could be very useful to know the direction of remanent magnetism and the inferred age of the igneous rocks in a basin. Finally, we must emphasize that we are in the early stages of this very interesting field of paleomagnetism.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 398–411, 6 FIGS.

RESISTIVITY STUDIES OF METALLIFEROUS SYNTHETIC CORES*

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ABSTRACT

The observed resistivities of synthetic cores comprising disseminated test lead particles, quartz sand grains, and commercial cement (25% by volume) and saturated with NaCl solutions are apparently best represented by a relationship similar to that of an electrically parallel circuit. The empirical relationship that best approximated the experimental data is:

$$\frac{1}{\rho_t} = \frac{\alpha}{\rho_{Pb}} + \frac{1}{F_P \rho_w},$$

where ρ_t is the observed resistivity of the core; ρ_{Pb} is the resistivity of the lead; F_P is the formation factor that the core would have if none of the solid materials were conductive; ρ_w is the resistivity of the saturating conductive fluid; and α is a parameter dependent upon the fractional volume of the fluid (ϕ_w), the fractional volume of lead (ϕ_{Pb}), and other factors. These experiments indicate that α can be approximated as follows:

$$\alpha \approx C 10^{100\phi_w} (\phi_{Pb})^K,$$

where C and K are "constants" for these particular experimental conditions.

It was found that the observed resistivity varies markedly with changes in either lead content or the fractional volume of saturating conductive fluid. At low values of the fractional volume of lead, the current conduction through the cores is largely electrolytic, and the observed resistivity is strongly influenced by changes in the fractional volume of the saturating fluid. When the fractional volume of the saturating fluid is maintained relatively constant and the lead content is increased, the observed resistivity decreases because some of the current is conducted through the lead particles by electronic conduction.

INTRODUCTION

The observed resistivity of a rock saturated with a fluid is dependent on the constituent materials of the rock, the fluid filling the pore space of the rock, and the tortuous path of current flow through the rock. To interpret resistivity data quantitatively, it is necessary to know how the constituent materials of a rock affect its resistivity. Although much work has been done to show how the observed resistivity is affected by the presence of argillaceous materials in rocks, little is known of how the observed resistivity is affected by the presence of metallic conductors in the rock matrix. This aspect of the problem of the interpretation of resistivity data is of paramount importance in mining geophysics. The object of this study was to investigate the observed resistivity of synthetic cores that have particles of metal disseminated in their matrices, and to determine if an empirical relationship could be found to relate the amount of metal to the observed resistivity of a given core. The ultimate goal of the research is to find a method of

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prognosticating the amount of metal in a rock from measurements of its resistivity.

Archie (1942) established an empirical relationship between the observed resistivity of a rock saturated with a conductive fluid and the resistivity of the saturating fluid. This relationship, now known as Archie's law, is given by the expression

$$\rho_t = F_A \rho_w, \tag{1}$$

where ρ_t is the observed resistivity of the rock resulting from direct measurements; ρ_w is the resistivity of the saturating fluid; and F_A is a dimensionless quantity which Archie called the "formation resistivity factor." Archie also found that the formation factor is empirically related to ϕ_w, the fractional volume of the rock occupied by the saturating fluid, by the relationship

$$F_A = \phi_w^{-m}, \tag{2}$$

where m is a constant designated the "cementation factor" for any particular rock. Archie assumed F_A to be constant for any given rock.

Patnode and Wyllie (1950) showed that the formation factor as defined by Archie can be considered a constant only if the rock matrix were entirely nonconductive. Since many rocks may contain argillaceous materials having considerable conductance when in an aqueous mixture, they reasoned that these materials would influence the determination of the formation factor. They performed a series of experiments on clay-electrolyte slurries and sandstones that led them to conclude that the formation factor decreases as the resistivity of the saturating fluid increases. They postulated the relationship

$$\frac{1}{\rho_t} = \frac{1}{\rho_f} + \frac{1}{\rho_e} = \frac{1}{\rho_f} + \frac{1}{F_P \rho_w} \tag{3}$$

to express the observed resistivity, ρ_t, of a rock containing "conducting solid materials." Here, ρ_f is the "resistivity due to the conductive solids as distributed in the core"; ρ_e is the "resistivity of the fluid as distributed in the core"; and $\rho_e = F_P \rho_w$, where ρ_w is the resistivity of the saturating fluid, and F_P is the formation factor that would be found if none of the solid materials were conductive. They further concluded that the observed resistivity of the conducting solid materials, ρ_f, of any particular system is a constant independent of the normality of the saturating fluid.

De Witte (1950) proposed that the experiments of Patnode and Wyllie showed only that the observed resistivity of a rock could be represented by an equation of the type

$$\frac{1}{\rho_t} = Z + \frac{Y}{\rho_w} \tag{4}$$

and that their experiments gave no conclusive information regarding the quantities Z and Y. De Witte suggested further that a homogeneous mixture of conductive solids and an electrolyte behaves as a mixture of two electrolytes. He postulated, from deductive reasoning and experimentation, that the observed resistivity of such a mixture of conductive solids and an electrolyte can be expressed by

$$\frac{1}{\rho_1} = \frac{X_s}{\rho_s} + \frac{X_w}{\rho_w} = \frac{1 - X_w}{\rho_s} + \frac{X_w}{\rho_w}, \tag{5}$$

where X_s is the fractional volume of the conductive solids; X_w is the fractional volume of the saturating fluid; and ρ_s is the resistivity of the conducting solid materials saturated with the fluid.

Berg (1952) showed from experiments that when the conducting solids are clays, the observed resistivities of the slurries are not independent of the normality of the saturating fluid. He also showed that the Patnode-Wyllie equation (3) and the De Witte equation (5) are essentially the same.

Howell (1953) discussed many of the factors that affect the path of current flow through a rock. He reasoned that the observed resistivity of a rock containing conducting minerals would be less than that of an otherwise identical rock containing no conducting minerals, because the conducting minerals would allow the current to bypass some of the more tortuous pores of the rock and hence reduce the observed resistivity. He postulated that the conductive minerals might make the geometric tortuosity, ordinarily a fundamental property of the rock itself and independent of saturation, a variable dependent upon the ratio of the resistivity of the electrolyte to that of the conducting grains and the amount and distribution of the conducting grains in the rock. Howell gave no experimental evidence to indicate the relative importance of these solid mineral conductors on the observed resistivity of a rock.

METHOD OF SYNTHESIZING CORES

Since it is difficult to obtain rocks containing solid mineral conductors distributed uniformly throughout their matrices, synthetic cores were fabricated to simulate this condition. The synthetic cores comprised disseminated test lead particles as the metallic conductor, quartz sand grains, and commercial cements. The test lead particles had an average size of 0.50 mm and were obtained by separation between 35- and 48-mesh screens. The quartz sand grains, which were screened from the Ottawa sand, had an average grain size of 0.42 mm. Three different commercial cements, furnished by the General Refractories Company, Philadelphia, Pennsylvania, were used. Lumnite cement has approximately a one-to-one ratio of calcium and aluminum oxides and small percentages (3 to 12 percent each) of silicon dioxide and iron oxide admixed. Grefco cement has a one-to-one ratio of calcium and aluminum oxides and is essentially free of other compounds. Alcoa cement has a one-to-two ratio of calcium and aluminum oxides and is relatively free of other compounds. Throughout this paper the metalliferous

synthetic cores are designated as Lumnite, Grefco, or Alcoa cores, according to the type of cementing material used.

The amounts of lead, quartz grains, and cement were predetermined so that the fractional volume of cement used in making each core was fixed at 0.25 in proportion to the total volume of the lead-quartz-cement mixture used; whereas the volumetric amounts of lead and quartz grains were varied relative to each other, yet together they always constituted 0.75 of the total volume of the lead-quartz-cement mixture. In these volumetric determinations, the densities of the lead, quartz, and dry cements were assumed to be 11.0, 2.6, and 2.6 gm/cm^3, respectively.

The materials were put in a beaker and stirred, while dry, until a homogeneous mixture was obtained. An amount of distilled water equivalent to approximately 20 per cent of the volume of the cement was then added, and the resulting mixture was stirred until homogeneous. This mixture was placed in a $\frac{7}{8}$-inch-diameter die and pressed under a pressure of 12,000 pounds per square inch. Most of the cores thus formed were about 1 cm in length. Three cores were generally made for every core composition that was to be investigated.

After pressing, the cores were kept for 3 or 4 days in air at atmospheric pressure and 100 per cent humidity while the cement hardened. The cores were next dried for 3 days in an oven at 100°C. After drying, the cores were repeatedly saturated with distilled water until they came to a constant weight (within 10 milligrams) indicating that all of the cement had reacted chemically with the water. During this process, the fractional volume of the saturating fluid for each core was calculated from its difference in weight before and after saturation with distilled water and from the physical dimensions of each core.

Since the above values of the densities were assumed and used in predetermining the amounts of the constituent materials of the cores, the fractional volumes of the solid materials in each of the synthetic cores as given in this paper are slightly different from what the absolute fractional volumes would be. Calculations showed that the fractional volumes of lead used in this investigation did not differ from the absolute fractional volumes by more than 5 per cent. Since a correction for this error would not materially affect the results of this investigation, all data are presented using the uncorrected predetermined values of fractional volumes of lead.

EXPERIMENTAL METHODS

To saturate the cores with a conductive fluid, the air was evacuated from the cores to a pressure of approximately 2 millimeters of mercury for a period of about one hour. The conductive fluid was introduced into the system at atmospheric pressure, which forced the liquid into the pore spaces.

All resistivity measurements of the saturating fluids were made with a Sunderman pipette-type conductivity cell. The resistivity measurements for samples of any individual saturating fluid that were taken from both the top and bottom

of the desiccator containing the saturated cores agreed within 1 per cent. The temperature of the saturating fluids at the time of the resistivity measurements was 20°C. ± 2°.

After saturation, the cores were taken out of the saturating solution, and the fluid adhering to the surfaces of the cores was removed by blotting. The saturated cores were placed in a brass *C*-clamp, which was connected to the measuring terminals of an impedance bridge (Fig. 1). The faces of the *C*-clamp were silver-plated to prevent corrosion, and blotters saturated with the saturating fluid of the cores were placed between a core and these faces in order to insure a good electrical contact.

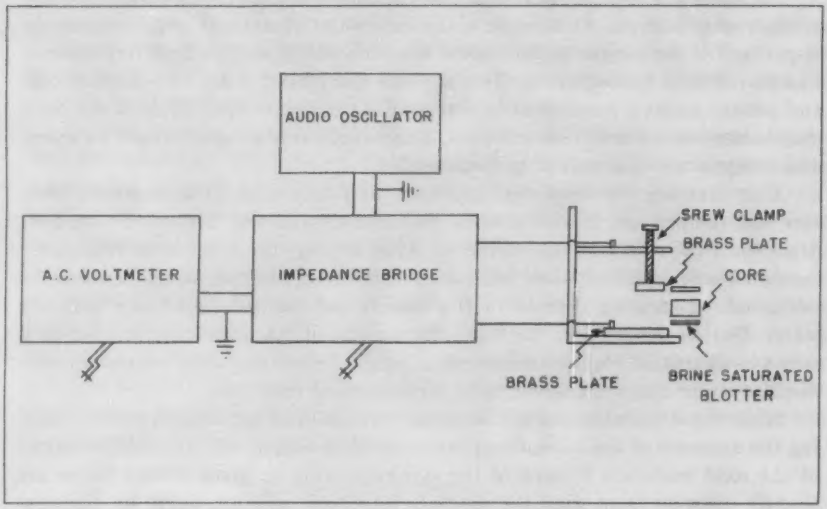

FIG. 1. Block diagram of experimental equipment.

Resistance measurements of these synthetic cores were taken with an impedance bridge excited by an oscillator set at 1,000 cps to keep electrode polarization effects at a minimum. The electrical resistance of each of the cores was read directly from the dials of the impedance bridge. The resistivity was calculated from this resistance and the physical dimensions of each core.

It was found that great care must be exercised when stirring the materials used to make the synthetic cores because the lead was much heavier and had a tendency to settle to the bottom of the stirring vessel. This was partially circumvented by re-stirring the materials before pressing each core, but the scatter of the data indicates that perfect reproducibility was not obtained for any two cores having the same quantities of constituent materials. The average deviation of the observed resistivities of cores having the same constituent materials was 10 percent.

EXPERIMENTAL RESULTS

For each group of synthetic cores, which are classified according to the type of cementing material used, the experimental results are shown graphically by plotting on linear graphs the observed resistivities against the fractional volume of lead, and the fractional volume of fluid against the fractional volume of lead. For these graphs, smooth curves were drawn through the data.

Lumnite Cores

For the group of synthetic cores containing Lumnite cement, the fractional volumes of lead (ϕ_{Pb}) were zero, 0.02, 0.04, 0.06, 0.08, 0.10, 0.14, and 0.20. These cores were saturated with a NaCl solution having a resistivity of 0.94 ohm-meter.

Figures 2a and 2b indicate that as the fractional volume of fluid is maintained essentially constant at a value slightly less than 0.15 and as the value of the fractional volume of lead is increased from zero to 0.02, the value of the observed resistivity of the synthetic cores decreases from about 57 ohm-meters to about 45 ohm-meters. This decrease in observed resistivity is attributed to the bypassing of some of the current through the lead particles, because of metallic conduction, thus shortening the more tortuous path that would otherwise be involved in electrolytic conduction alone. However, for this small fractional volume of lead the conduction through the cores is probably largely electrolytic.

As the value of the fractional volume of lead is increased further from 0.02 to 0.08, the value of the fractional volume of the fluid decreases from about 0.15 to about 0.13 presumably because of packing effects in this range of lead content. Because the conduction in this range of the fractional volume of lead is still probably largely electrolytic, the effect of this reduction in the fractional volume of fluid is to increase the observed resistivities of the cores from a value of about 45 ohm-meters to slightly more than 60 ohm-meters.

As the value of the fractional volume of the lead is increased above 0.08, the values of the observed resistivities decrease in spite of the fact that the fractional volume of the fluid decreases.[1] However, in this range of lead content (see Figs. 2a and 2b), the change in fluid content per unit change in lead content is smaller than it is for fractional volumes of lead less than 0.08.

Neglecting any possible conduction along the surface of the cores and assuming that the quartz grains and the hardened cement are non-conductors, it is reasoned that the behavior of the observed resistivity of the cores as discussed above is analogous as a first approximation to an electrically parallel circuit. This circuit would comprise the resistivity of the saturating fluid and the resistivity of the lead. This assumption is oversimplified because the saturating fluid and the lead are not isolated conductors in parallel circuits but in reality are a group of

[1] The unusually large variation of observed resistivity for two of the cores with a fractional volume of lead of 0.20 (Fig. 2a) is probably due to attempts made to flush the cores under pressure with distilled water in order to clean them. It is thought that this operation affected the pore distribution, and it was not used again.

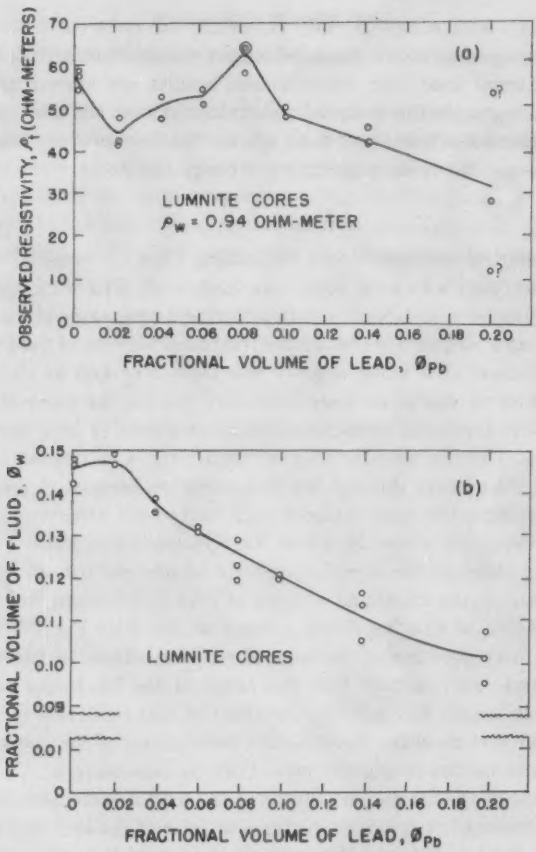

FIG. 2. (a) Plot of the observed resistivity (ρ_t) versus the fractional volume of lead (ϕ_{Pb}) for the Lumnite cores. (b) Plot of the fractional volume of fluid (ϕ_w) versus the fractional volume of lead (ϕ_{Pb}) for the Lumnite cores.

interconnected circuits in which many of the elements of contrasting resistivity are in contact. Nonetheless, the observed resistivity data did indicate that by using as a guiding principle the concept of parallel electrical circuits as advanced by the afore-mentioned investigators, an empirical relationship that approximated the data could be obtained. This relationship is

$$\frac{1}{\rho_t} = \frac{\alpha}{\rho_{Pb}} + \frac{1}{F_P \rho_w}, \tag{6}$$

where ρ_t is the observed resistivity of the core; ρ_{Pb} is the resistivity of the lead; F_P is the formation factor that the core would have if none of the solid materials

were conductive; ρ_w is the resistivity of the saturating fluid; and α is a parameter of the electrical system.

Equation (6) was solved for α, and known values were substituted into ρ_t, ρ_{Pb}, F_P, and ρ_w for a number of cores containing different amounts of lead. These values of α were plotted on linear graph paper against the fractional volume of lead in order to find whether a simple relationship existed between them. It was found that such a relationship would be complicated. Figures 2a and 2b showed that α was strongly dependent upon the fractional volume of the saturating fluid. Assuming that α was in some way related to the fractional volume of lead, and knowing that it was dependent on the fractional volume of fluid, the following relationship was obtained through successive trial calculations:

$$\alpha \approx 10^{100\phi_w} f(\phi_{Pb}), \tag{7}$$

where $f(\phi_{Pb})$ is a function of the fractional volume of lead in the cores. This quantity was substituted for α in equation (6) and solved for $f(\phi_{Pb})$. Equation (8) resulted from this operation.

$$f(\phi_{Pb}) \approx \frac{\rho_{Pb}(F_P\rho_w - \rho_t)}{F_P\rho_w\rho_t 10^{100\phi_w}} \tag{8}$$

In equation (8) all of the parameters on the right side are directly measurable in the laboratory except F_P. To calculate F_P for each Lumnite core, first the formation factor F_A, as defined by Archie, was calculated for the cores containing a fractional volume of Lumnite cement of 0.25 and a fractional volume of quartz grains of 0.75 (that is, no lead was present) by using equation (1); then using equation (2) and the average value of the fractional volume of fluid in these cores, the value of the cementation factor, m, was found to be 2.13. This value of m was assumed to remain constant for all Lumnite cores for all fractional volumes of lead used. Therefore, by using this value of m and the appropriate value of the fractional volume of fluid (ϕ_w), the average formation factor F_P for cores having the same composition was calculated by the formula $F_P = (\phi_w)^{-m}$. The resistivity of lead was taken as 22.0×10^{-8} ohm-meter (Hodgman, 1950).

Using equation (8), the function $f(\phi_{Pb})$ was calculated for all the Lumnite cores and plotted on logarithmic paper against the fractional volume of lead (Fig. 3). The straight line, which was obtained by the method of least squares, is given by

$$f(\phi_{Pb}) = C(\phi_{Pb})^K, \tag{9}$$

where C and K are "constants"; and ϕ_{Pb} is the fractional volume of lead. For this suite of Lumnite cores, $K = 5.28$, and $C = 4.57 \times 10^{-18}$.

The fractional volume of lead can therefore be obtained by equating equations (8) and (9) to give:

$$\phi_{Pb} = \left[\frac{\rho_{Pb}(F_P\rho_w - \rho_t)}{CF_P\rho_w\rho_t 10^{100\phi_w}}\right]^{1/K} \tag{10}$$

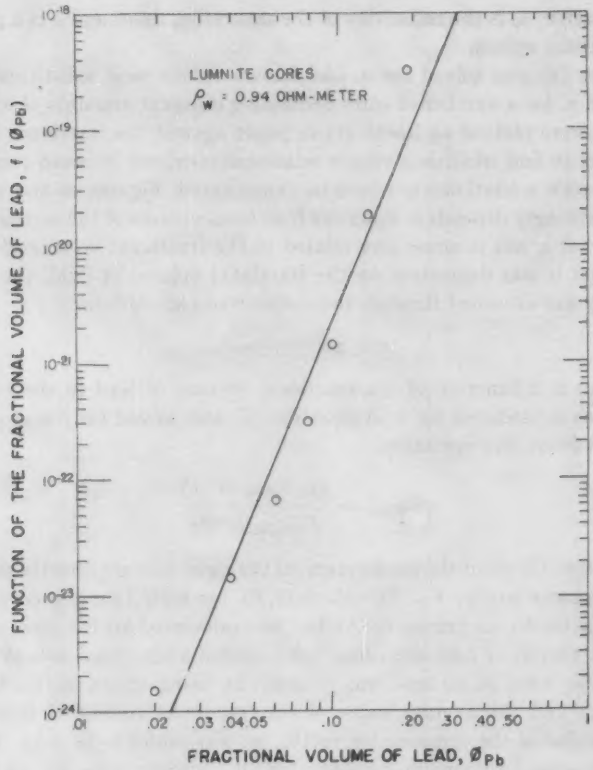

FIG. 3. Plot of the function of the fractional volume of lead $f(\phi_{Pb})$ versus the fractional volume of lead (ϕ_{Pb}) for the Lumnite cores.

TABLE I

COMPARISON OF ACTUAL AND CALCULATED VALUES OF THE FRACTIONAL VOLUME OF LEAD IN THE LUMNITE CORES

Actual fractional volume of lead	Calculated fractional volume of lead	Percent difference
0.020	0.025	25
0.040	0.038	5
0.060	0.051	15
0.080	0.068	15
0.10	0.085	15
0.14	0.15	4
0.20	0.25	25
	Average percent difference =	15

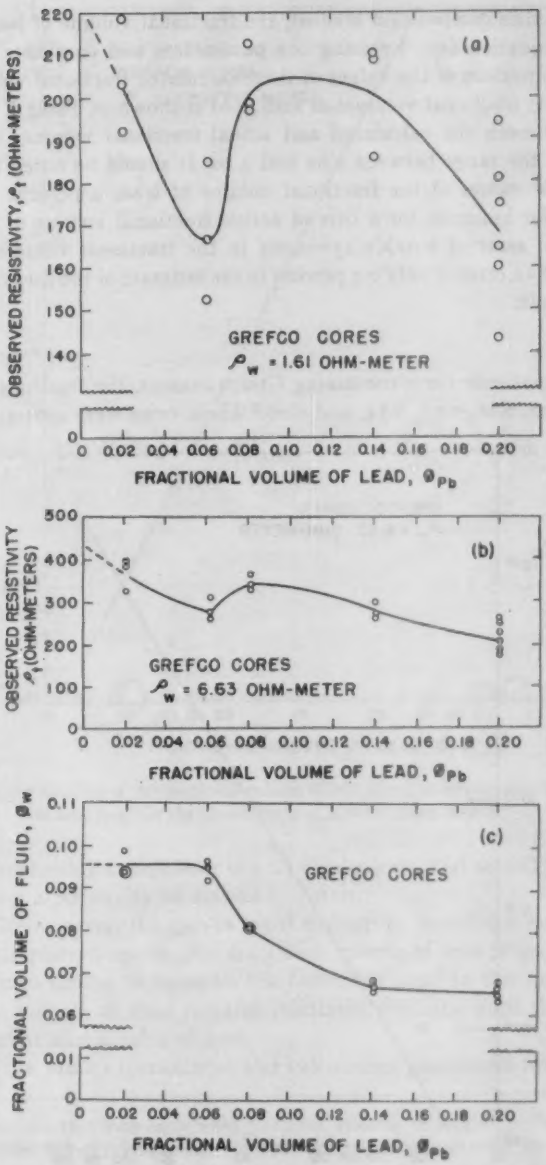

FIG. 4. (a) Plot of the observed resistivity (ρ_t) versus the fractional volume of lead (ϕ_{Pb}) for the Grefco cores at $\rho_w = 1.61$ ohm-meters. (b) Plot of the observed resistivity (ρ_t) versus the fractional volume of lead (ϕ_{Pb}) for the Grefco cores at $\rho_w = 6.63$ ohm-meters. (c) Plot of the fractional volume of fluid (ϕ_w) versus the fractional volume of lead (ϕ_{Pb}) for the Grefco cores.

For each core composition studied, the fractional volume of lead was calculated from equation (10) by using the parameters and constants as discussed above. A comparison of the values of these calculated fractional volumes of lead and the actual fractional volumes of lead used is shown in Table I. The average difference between the calculated and actual fractional volumes of lead is 15 percent over the range between 0.02 and 0.20. It should be noted that at these relatively low values of the fractional volume of lead, a percent difference of 25 percent, for example, for a core of actual fractional volume of lead of 0.02, represents an error of $0.02 \times 0.25 = 0.005$ in the fractional volume of the lead and therefore an error of only 0.5 percent in the estimate of the lead content of the core as a whole.

Grefco Cores

For the synthetic cores containing Grefco cement, the fractional volumes of lead were 0.02, 0.06, 0.08, 0.14, and 0.20.[2] These cores were saturated first with

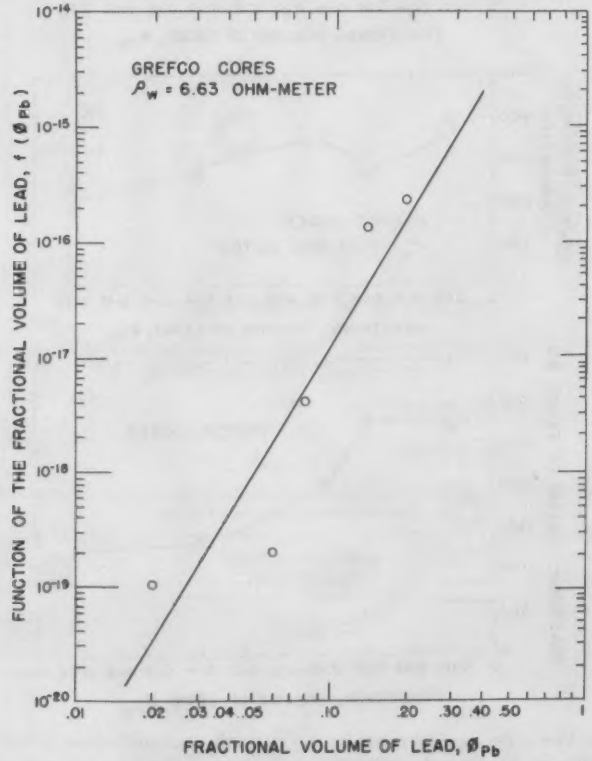

FIG. 5. Plot of the function of the fractional volume of lead $f(\phi_{Pb})$ versus the fractional volume of lead (ϕ_{Pb}) for the Grefco cores at $\rho_w = 6.63$ ohm-meters.

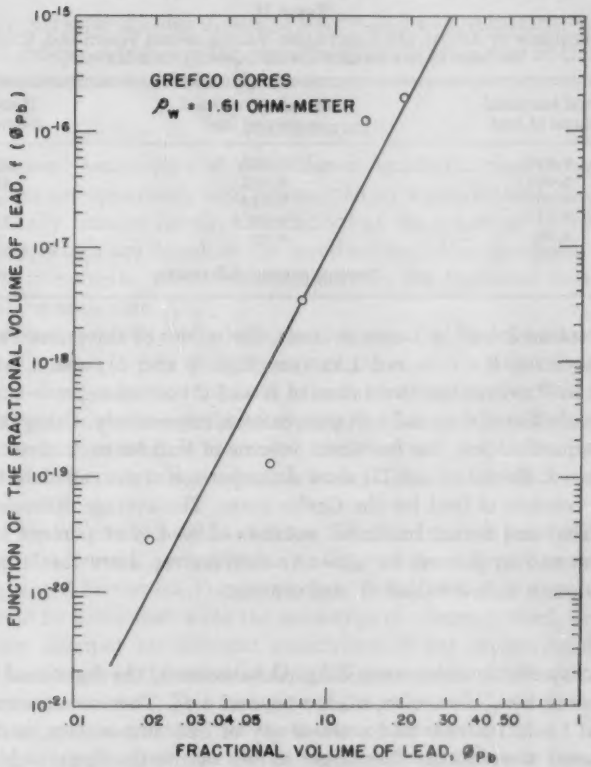

FIG. 6. Plot of the function of the fractional volume of lead $f(\phi_{Pb})$ versus the fractional volume of lead (ϕ_{Pb}) for the Grefco cores at $\rho_w = 1.61$ ohm-meters.

a NaCl solution having a resistivity of 6.63 ohm-meters, and second with a NaCl solution having a resistivity of 1.61 ohm-meters.

For the Grefco cores, the curves for the observed resistivity and fractional volume of fluid plotted against the fractional volume of lead (Figs. 4a, 4b, and 4c) show features similar to those for the Lumnite cores.[2] In this case, however, the fractional volume of fluid remains relatively constant until the fractional volume of lead attains a value of 0.06.

By using the same experimental and calculation procedures for the Grefco

[2] The Grefco cores that were made using fractional volumes of lead of zero and 0.04 were, unfortunately, either broken or contaminated with foreign substances and could not be used in the experiments. Additional Grefco cement was not available at that time to make new cores.

[3] The values of the observed resistivity and the fractional volume of fluid for a zero value of the fractional volume of lead were extrapolated on the basis of the similar curves found for the Lumnite cement.

TABLE II

COMPARISON OF ACTUAL AND CALCULATED VALUES OF THE FRACTIONAL VOLUME OF LEAD IN THE GREFCO CORES (ρ_w=6.63 OHM-METERS)

Actual fractional volume of lead	Calculated fractional volume of lead	Percent difference
0.020	0.027	35
0.060	0.033	45
0.080	0.073	9
0.14	0.19	34
0.20	0.22	9
	Average percent difference=	26

cores as were used for the Lumnite cores, the values of the parameters were as follows: $m=2.20$; $K=3.70$ and 4.22 (see Figs. 5 and 6), and $C=6.51\times10^{-14}$ and 1.53×10^{-13}, where the two values of K and C correspond to saturating electrolyte resistivities of 6.63 and 1.61 ohm-meters, respectively. Using these parameters and equation (10), the fractional volume of lead for each core composition was calculated. Tables II and III show a comparison of the calculated and actual fractional volumes of lead for the Grefco cores. The average difference between the calculated and actual fractional volumes of lead is 26 percent for $\rho_w=6.63$ ohm-meters and 19 percent for $\rho_w=1.61$ ohm-meters. Here the largest percent differences occur at low values of lead content.

Alcoa Cores

For the synthetic cores containing Alcoa cement, the fractional volumes of lead were zero, 0.04, 0.10, 0.20, 0.40, 0.60, and 0.75. These cores were saturated with a NaCl solution that had a resistivity of 13.8 ohm-meters, and resistivity measurements were taken. The larger values of the fractional volume of lead were used in this suite of cores to ascertain whether the empirical relationship given by equation (10)—which was deduced originally from studies on the suite of Lumnite cores only and which held for the Grefco cores—was valid also at much higher values of lead content. It was found that equation (10) held, within the same limits of accuracy, for these fractional volumes of lead. The values of

TABLE III

COMPARISON OF ACTUAL AND CALCULATED VALUES OF THE FRACTIONAL VOLUME OF LEAD IN THE GREFCO CORES (ρ_w=1.61 OHM-METERS)

Actual fractional volume of lead	Calculated fractional volume of lead	Percent difference
0.020	0.025	25
0.060	0.036	40
0.080	0.079	1
0.14	0.18	29
0.20	0.20	0
	Average percent difference=	19

C and K for this suite of cores were 2.00×10^{-14} and 10.5, respectively. The average percent difference between the actual and calculated values of the fractional volume of lead in these cores was 22 percent.

CONCLUSIONS

The observed resistivities of metalliferous synthetic cores saturated with NaCl solutions are apparently best represented by a relationship similar to that of an electrically parallel circuit. Calculations of the fractional volumes of lead in these cores, which are based on the resulting empirical equations, show that it is possible to estimate, within reasonable limits, the fractional volume of lead used in making each core.

The observed resistivity data indicate that at low values of lead content, the current conduction is largely electrolytic, and the observed resistivity is strongly influenced by changes in the fractional volume of the saturating fluid. However, when the fractional volume of the saturating fluid is maintained relatively constant and the lead content is increased, the observed resistivity decreases because some of the current is conducted through the lead particles by metallic conduction.

The fact that the values of C and K are different for each suite of cores made with different cements is probably due mainly to the different packing effects and consequent different fractional volumes of fluid for each type of cement. Also, it should be noted that when the same type of cement is used, the values of C and K are different for different resistivities of the saturating electrolyte. However, the changes of the values of C and K are less than those observed when different cements are used. This variation of the values of C and K for the same type of cement may be the result of the scatter of the data.

It should be emphasized that the parameter α may prove to be much more complicated than given in this paper.

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GEOPHYSICS, VOL. XXII, NO. 2 (APRIL, 1957), PP. 412–433, 11 FIGS.

GEOPHYSICAL RESEARCH AND PROGRESS IN EXPLORATION*

MILTON B. DOBRIN† AND HENRY F. DUNLAP‡

ABSTRACT

This paper, the SEG Research Committee's second annual review of current developments in exploration geophysics, will emphasize research activities at universities and other non-commercial institutions which relate closely to geophysical exploration.

Industry developments worth noting in the seismic field include the considerable increase in use of magnctic recording, use of pressure-sensitive geophones with preamplifiers in the bay and marsh areas of the Gulf Coast, use of fathometer-type instruments to obtain near bottom layering in marine areas, and use of nonphotographic methods of reproducing seismic data. Considerable experimentation with weight dropping techniques, and with use of higher frequencies to get better resolution has continued during the past year. Use of models, particularly two dimensional models, is increasing.

There have been significant innovations in logging techniques, particularly in the use of in-hole accelerators for neutron generation, and in the development of in-hole equipment for measuring gamma ray spectra. The use of continuous velocity logs is increasing.

Academic research has been of two kinds. First, there are studies of basic physical principles underlying current or prospective exploration methods which could lead to improvements and new applications. Secondly, geophysical methods originally developed for petroleum exploration are being employed for large-scale investigations of the earth's crustal structure. These studies should contribute important information on the geology of such features as continental shelves, geosynclines, and mountain systems, information potentially useful to geologists for developing new concepts in exploration thinking. The two kinds of research illustrate the current interdependence between "pure" and "applied" geophysics.

Important research projects on scattering, statistical improvement of signal-to-noise, explosion-wave generation in the earth, and surface waves exemplify the activity going on in university laboratories today which may result in improved seismic exploration techniques tomorrow. Conversely, university-sponsored seismic and gravity investigations of the deep oceans, the continental margins and various western mountain chains illustrate how geophysics is contributing basic geologic information on a regional to global scale.

INTRODUCTION

At the 1955 Annual Meeting of the SEG in Denver, the Society's Research Committee sponsored a paper[1] which reviewed the significant technical developments in exploration geophysics during the previous year. In making plans for the present paper, the members of the Committee realized that there would probably not be enough really new advances in exploration tools and techniques during the course of a single year to justify a paper on those topics alone. They recommended that the authors concentrate instead on the extensive geophysical research going on at universities and similar non-commercial institutions. This type of activity has contributed more than is generally realized to several fields of exploration, both geophysical and geological, and it should contribute to an even greater extent in the future. We shall accordingly devote most of our space in the current paper to academic research which relates directly or indirectly to

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[1] Dobrin, Milton B. and Van Nostrand, Robert G., 1956, Review of current developments in exploration geophysics: *Geophysics*, V. 21, p. 142–155.

exploration geophysics. Before discussing these developments, however, we would like to discuss some of the substantial progress that has been made in several fields of commercial geophysics during the past year.

DEVELOPMENTS IN OIL EXPLORATION

Magnetic Recording

The use of magnetic recording in seismic exploration has expanded spectacularly during the past year. Figure 1 shows the number of magnetic units which had been sold or were on order as of September. The cumulative total, 472, should be compared with last year's cumulative figure of 181, showing that 291 units have been delivered or ordered during the past 12 months.

It is noteworthy indeed that enough magnetic recording units have been

TOTAL MAGNETIC RECORDING EQUIPMENT

MANUFACTURERS REPORTING: 10

TOTAL SYSTEMS	472
SYSTEMS WITH DYNAMIC TIME SHIFT	50
CENTRAL OFFICE SYSTEMS	25
PERCENTAGE MAGNETIC CREWS	52%

FIG. 1. Statistics on magnetic recording equipment delivered or on order as of September 1, 1956.

delivered or are on order to equip every other seismic crew now operating in the world. Most of the playback units in current use have a provision for static time shifting and 50 of them include equipment for dynamic shifting, which allows a variable adjustment for normal moveout with increasing time on the record.

Instrumentation for Water Work

Two important new types of seismic equipment have recently gone into use for marine prospecting. Pressure-sensitive detectors with preamplifiers have proved to be more effective in shallow water and marsh areas of the Gulf Coast than the conventional velocity-type detectors. Figure 2 shows a comparison of the record obtained in shallow water with one pressure-sensitive phone per trace (10 bottom traces) with that from a spread of eleven velocity-type phones per trace (10 top traces). Great savings in time and somewhat better resolution of reflection events from the pressure phones are achieved by this method. Pressure detectors in marine work are not new, but they have not previously been used in very shallow water.

A more novel development in offshore exploration is the "Marine Sono-

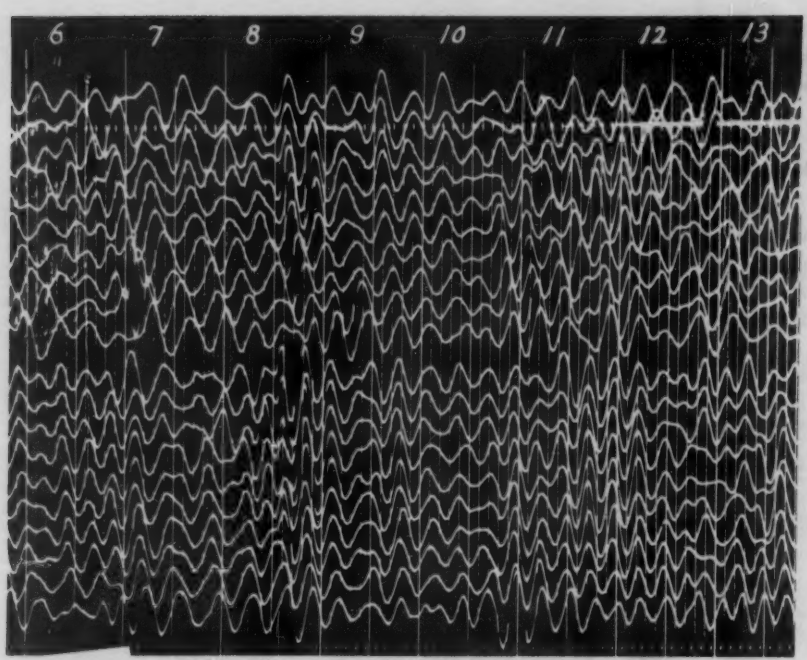

FIG. 2. Comparison of data obtained using a single pressure-sensitive detector per trace (10 bottom traces) with data obtained using 11 velocity-type detectors per trace (10 top traces) in water a few feet deep along the Louisiana coast.

probe." This is a fathometer-type instrument which indicates layering in the first few hundred feet below the ocean bottom. It employs a magnetostrictive source about two feet in diameter and a ceramic crystal pickup. The generator gives out 12 pulses per second with a peak power of three quarters of a megawatt. The device is mounted in the bottom of a boat and the recorder gives a continuous profile showing the sub-bottom structure directly, as is illustrated in Figure 3. This shows two buried reefs which cause draping in the sediments above; the draping dies out as we go upward to the ocean bottom. Thus the reefs would not have been detectable from bottom topography alone. Figure 4 shows several profiles over a shallow salt dome from which a pinnacle of cap rock projects upward into the water. Note the well-defined boundary between the cap rock and the salt.

Miscellaneous Seismic Developments

There has been some revival of interest in refraction work recently, particularly in foreign work. One operator has been successfully using character analysis

of refracted waves to obtain information on the type of lithology encountered in new sedimentary basins. Instrumentation with frequency response as low as 2 or 3 cycles per second is used in this work. These low frequency refractions have also proven quite useful in mapping the flanks of salt domes to depths of 11,000 feet using 12 to 15 miles of offset at the surface.

Considerable work is going on to develop nonphotographic means of recording and reproducing seismic information. One of these methods is based on the "Electrofax" process of RCA, employing photo-conductive paper. This paper is given an electrical charge and then exposed to light. Where the image falls on the paper, the electrical charge is dissipated, forming a latent image. A fine powder which is both opaque and electrically charged is then dusted over the paper which makes the latent image visible. The image is fixed by a heat process employing no chemicals. It is expected that a seismic camera employing a process similar to this will be available in the near future. A somewhat different process uses Western Union "Teledeltos" paper in which a white layer covering a dark surface is removed by application of an electric current through a stylus. These methods have the great advantage of simplicity and freedom from darkroom procedures in the field.

Work on weight-dropping techniques has been continued with emphasis on

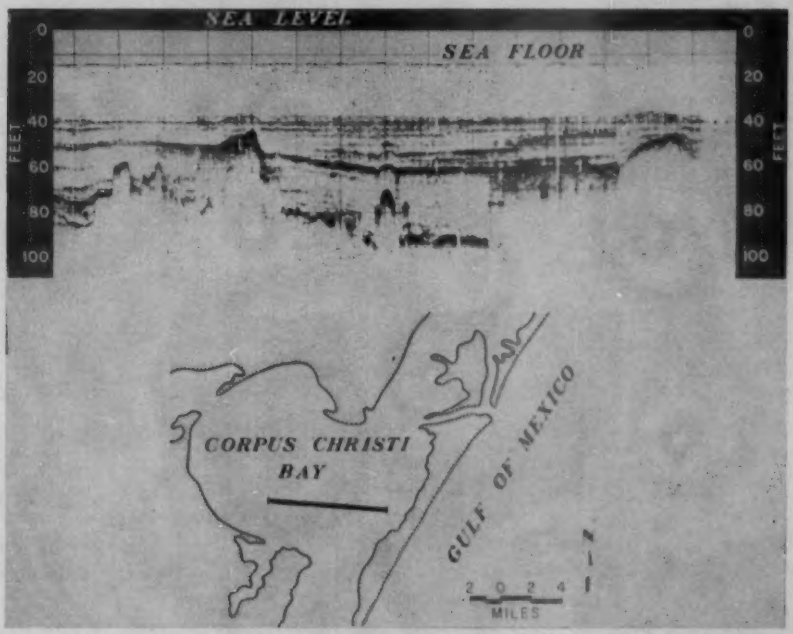

FIG. 3. Marine Sonoprobe profile in Corpus Christi Bay, showing buried reefs and associated draping of the sediments above them.

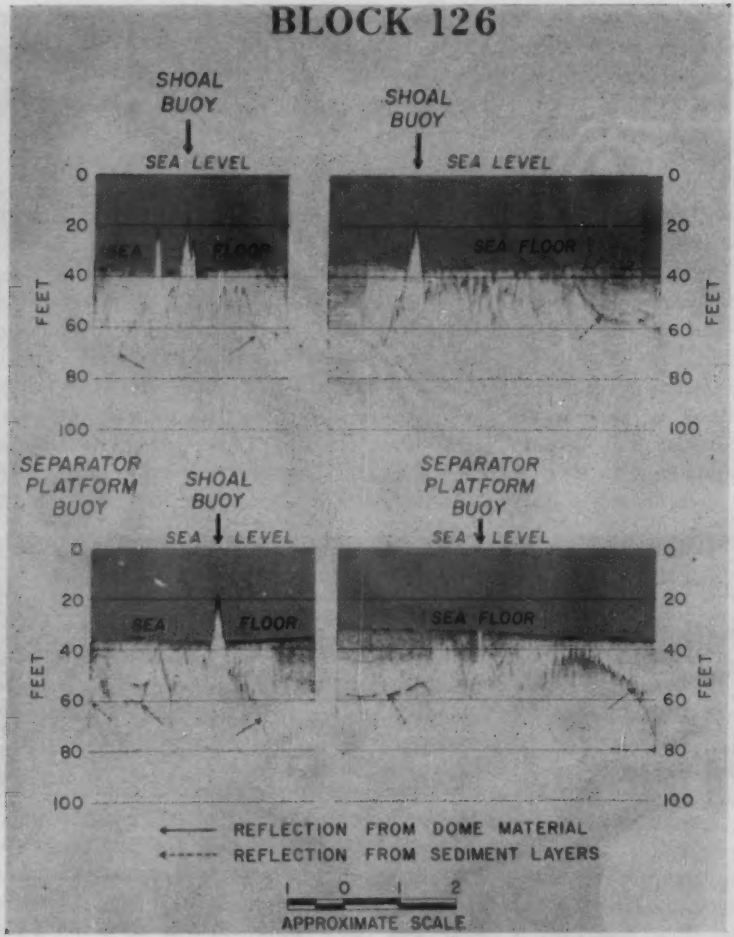

FIG. 4. Marine Sonoprobe profiles over a shallow salt dome off the Louisiana Coast.

methods for more effective compositing of data and methods for eliminating ground roll generated by the drop. Figure 5 is an example of what one company is using for a weight truck. The weight is dropped between the wheels in this case. The operators state that this significantly improves the signal-to-noise ratio by reducing truck oscillations on release.

Several companies have continued exploring the usefulness of higher frequencies in shallow seismic work which requires high resolution. Remarkable depths of penetration have been reported in a few cases, but the penetration is

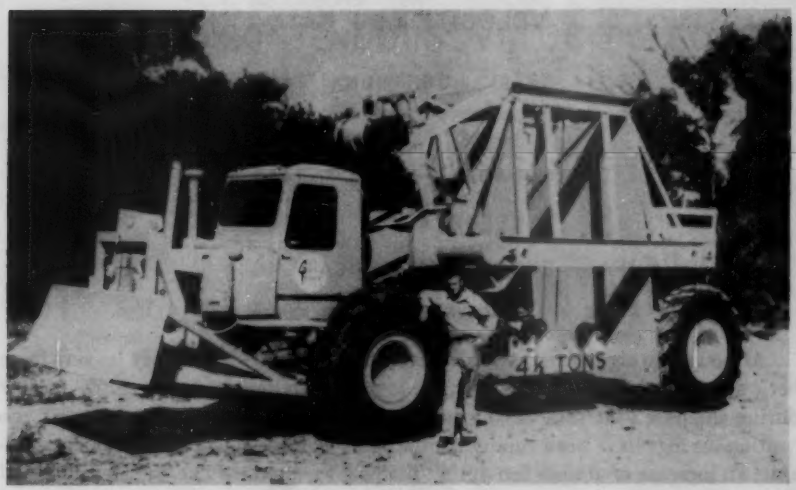

FIG. 5. Large equipment used in weight-dropping work. The special frame of this vehicle permits the weight to be dropped between the wheels. This reduces undesirable truck oscillations on release.

normally limited to 5,000 feet or less at frequencies over 100 cps. The effect of the near surface is unusually important in high frequency work, and precludes use of the technique in some areas.

Use of seismic models as a general research tool in the industry is spreading rapidly. Two-dimensional models are particularly convenient and have found use in studying a large class of problems which cannot be treated by the "geometrical optics" approach.

Borehole Geophysics

So much for above-ground exploration. There is, however, a quite different field properly described as exploration which is concerned with measurements made in boreholes. Some rather exciting developments both from the standpoint of instrumentation and concept have occurred in this field during the past year.

To cite one example, accelerators have been developed which are so small that they can be lowered into a borehole to produce neutrons by nuclear reactions, which makes for more efficient neutron logging. The most commonly used reaction is deuterons on tritium. This reaction yields 14 mev neutrons at low bombarding energy with practically no gamma rays. Photomultiplier tubes and scintillation crystals have been developed for borehole use which can measure gamma ray spectra. These make it possible to select only that radiation which is characteristic of a particular element or group of elements under investigation, thus enabling one to determine the chemical compositions of the formations penetrated by the borehole.

VELOCITY LOG DATA

TOTAL LOGS RUN	1432
U.S.	877
CANADA	455
VENEZUELA	60
EUROPE & N. AFRICA	40

FIG. 6. Statistics on continuous velocity logging as of September 1, 1956.

Although no significant new technical improvements in velocity loggers have been announced, the number of wells logged with this tool was much greater during the past year than in any previous year. Figure 6 shows that over 1,400 continuous logs have been run by the oil industry since this service became available, an increase of almost 800 during the past 12 months. The 407 logs obtained in the United States represent 2.7 percent of wildcats drilled in the United States during the 1955 calendar year, according to Lahee's figures. These logs have been used to an increasing extent for stratigraphic identification and for correlation.

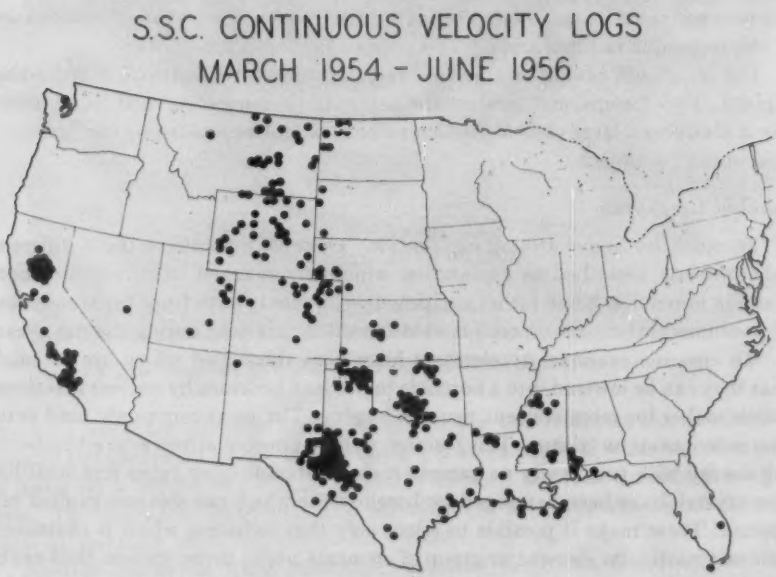

FIG. 7. Geographical distribution of continuous velocity logs run in the U. S. by one service company. About half of the U. S. logs are represented here.

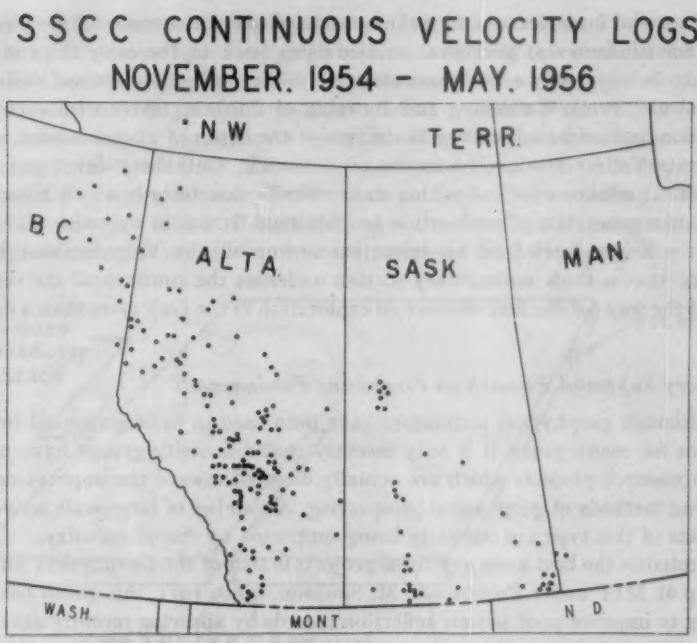

FIG. 8. Geographical distribution of continuous velocity logs run in Canada by one service company. About half of the Canadian logs are represented here.

Figures 7 and 8 give some idea of the geographic distribution of these velocity logs in the United States and in Canada. These represent logs run only by the Seismograph Service Corporation, but might be considered a sample of the industry. In this connection, it would be helpful if the summaries of wells in which velocity data have been obtained, published occasionally in GEOPHYSICS, could indicate which wells have the continuous velocity logs run in them. There is no convenient source for these data at present.

CURRENT GEOPHYSICAL RESEARCH AT NON-COMMERCIAL INSTITUTIONS

Now that we have discussed a number of the more significant geophysical developments from the oil industry, we shall turn to the more fundamental geophysical research going on at non-profit institutions such as universities. It would be neither possible nor desirable to discuss all of these projects here. We feel, however, that there would be distinct advantages if a complete list of them, with brief descriptions of each, were made available to those interested. We are accordingly including such a list as an appendix to the present paper. For the body of the paper, we have chosen only a small number of these projects to illustrate some of the different kinds of geophysical work now going on outside of industry.

The use of instruments and techniques developed for commercial geophysical work for fundamental geological studies dates back to the early days of geophysics. In 1935, only a few years after the seismic reflection method went into general use, Profs. Gutenberg and Buwalda of Caltech conducted a successful reflection and refraction survey to determine the depth of glacial erosion in the Yosemite Valley. During the course of this work, Gutenberg developed some theoretical relations for computing data on reflection records which have been useful to a generation of exploration geophysicists. It was in 1935 also that Prof. Maurice Ewing carried on his refraction survey off the Virginia coast which showed that a thick sedimentary section underlies the continental shelves and paved the way for the first offshore oil exploration in the Gulf more than a decade later.

Industry Supported Research on Prospecting Fundamentals

Although geophysical techniques have been used in basic geological investigations for many years, it is only recently that university groups have undertaken research projects which are actually directed toward the improvement of existing methods of geophysical prospecting. A number of large-scale university projects of this type are currently being supported by the oil industry.

Probably the best known of these projects is that of the Geophysical Analysis Group at MIT under Professor S. M. Simpson. Since 1951, this group has been trying to improve poor seismic reflection records by applying recently developed statistical techniques such as auto-correlation and cross-correlation to record analysis. This work is being sponsored by a group of seven oil companies. Successful techniques have been developed for improving the appearance of reflections in the following cases:

1. Where the reflection is mixed with partially predictable noise of different properties from the reflection itself.
2. Where the reflection follows a path across the record which obeys the laws of geometric optics and where the noise in which it is immersed is random.

For the second case, a computing procedure using high-speed electronic equipment has been developed which produces a structural cross-section directly from the raw data. Methods of separating overlapping reflections are also being worked out. A by-product of this research has been a theoretical study of wave propagation through inhomogeneous media. This study could substantially extend the amount of geological information that can be derived from a seismogram.

A more recently established research activity of direct interest to exploration geophysicists is the program for investigating seismic scattering at the Institute of Geophysics of the University of California at Los Angeles. This program was set up on the initiative of the oil industry to obtain fundamental physical data on the process that may well account for most of the noise that obscures reflections in "no reflections" (N-R) areas. The studies, now in their second year,

have included both model experiments and theoretical analysis. Professor L. B. Slichter and Professor Leon Knopoff, who are in charge of this work, have kindly provided the next two figures, which illustrate one phase of the model work. Figure 9 is a schematic diagram of a model, consisting of a lucite sheet with two transducers, which was designed to investigate the diffraction of a seismic pulse around a barrier, in this case the slot. The transmitter is fixed in position but the receiver is moved along the right-hand edge from front to back. Waves reaching it when it is near the front are diffracted from the end of the slot. Figure 10 shows the seismic signals recorded at various detector positions. Note the simplicity of the

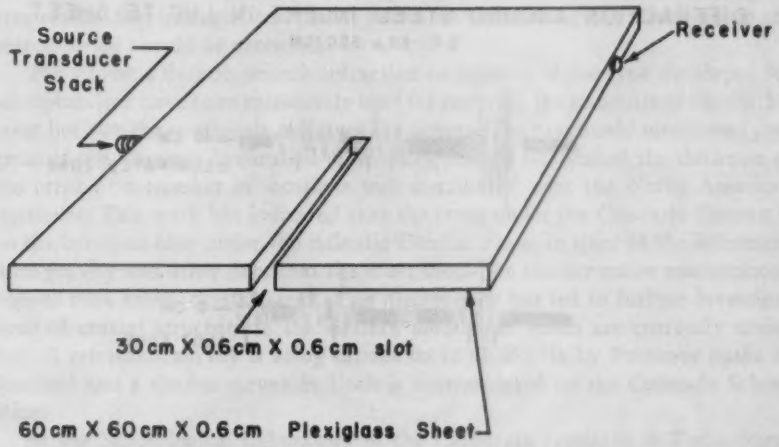

FIG. 9. One of the model set ups used in the U.C.L.A. seismic scattering project. This model is used to study the diffraction of a seismic pulse around the edge of a barrier.

diffracted wave form in the shadow zone compared to the legginess of the combined diffracted and direct wave in the illuminated zone. This effect has been predicted theoretically in a paper by Knopoff recently published in the *Journal of the Acoustical Society*. Instructive model experiments on scattering of seismic waves have also been carried out by Dr. H. E. Tatel of the Carnegie Institution of Washington in connection with a long-term program of studying the earth's crustal structure by recording large explosions at large distances. His experiments show that some of the noise on seismic records is generated when body waves from the explosion are converted to Rayleigh waves upon striking surface irregularities between the source and receiver. Additional model studies on diffraction around a barrier are being carried on at Lamont Geological Observatory.

Shothole Explosion Studies

Three universities are doing research on a problem that is important to all geophysicists engaged in seismic exploration, namely the mechanism by which an

explosion in the earth, whose intrinsic duration is less than a millisecond, yields oscillating seismic waves with periods ranging from tens to hundreds of milliseconds. More knowledge of this phenomenon might help in eliminating adverse shot-hole effects from seismic records. At Pennsylvania State University Prof. B. F. Howell, Jr. is leading a program for investigating ground motion near an explosion by measuring the energy in various types of waves and studying the conversion of energy from one type to another. At St. Louis University, an oil company has been supporting a long-term research program to determine energy-frequency relations near an explosion and also to study generation of shear waves

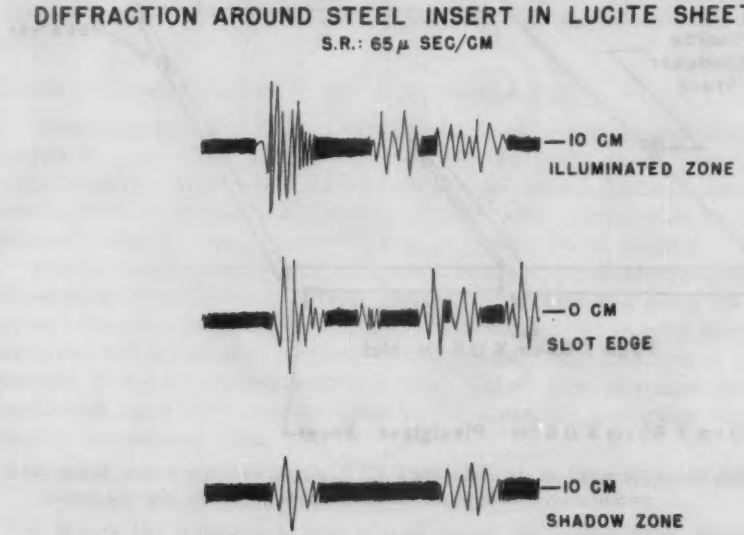

FIG. 10. Seismic signals recorded at various detector positions for model shown in Figure 9.

by blasts. A new project at the University of Utah involves a study of the relation between seismic wave characteristics and the size of the cavity created by the explosion.

Use of Geophysics in Regional Geologic Studies

Let us now consider some examples of geophysical studies at academic institutions where the object is primarily to obtain geological information. In most of this work the information resulting from such investigations differs from that sought by commercial geophysicists mainly in scale. Where the geophysicist exploring for oil is looking for structures with dimensions of the order of a few miles, his academic counterpart is more likely to be interested in the structure of larger-scale features ranging from regional basins or swells tens of miles across to conti-

nents or ocean basins thousands of miles wide. Yet on a long-term basis, the contribution of the so-called "pure" geophysicist to the discovery of oil may be as great or greater than that of the commercial geophysicist. Before extensive expenditures can be justified in exploring for oil in new areas, it is necessary to know where the sedimentary basins are located and the approximate thickness of the sedimentary section. Regional seismic, gravity, and magnetic surveys often give this type of information. One good example is the pioneering offshore seismic survey of Ewing which established the existence of a thick sedimentary section under the Atlantic shelf and directed the attention of the oil industry to offshore areas. Often such surveys furnish basic geological information which an imaginative exploration geologist can put to use in recommending new areas where the search for oil should be extended.

For almost a decade, seismic refraction techniques of the type developed for oil exploration have been extensively used for studying the structure of the earth's crust both on the continents and over the oceans. The previously mentioned program of the Carnegie Institution of Washington has established the thickness of the crust at a number of locations well distributed over the North American continent. This work has indicated that the crust under the Colorado Plateau is no thicker than that under the Atlantic Coastal Plain, in spite of the inferences from gravity and other data that the crust should be thicker under mountainous regions than under coastal areas. This discrepancy has led to further investigations of crustal structure in the western mountains which are currently under way. A refraction survey is being carried on in California by Professor Soske of Stanford and a similar survey in Utah is contemplated by the Colorado School Mines.

At the Seismological Laboratory of the California Institute of Technology, Prof. Frank Press is attacking the problem of crustal thickness variations by studying surface waves from distant earthquakes. He is measuring changes in the phase velocity of surface waves from the earthquakes as they travel across California from the coast into the mountains. To do this he is correlating records from earthquake observatories lying along the line of wave propagation in the same way that exploration geophysicists correlate traces from adjacent groups in a geophone spread. Figure 11 shows surface waves from a Pacific earthquake as recorded at three stations, Pasadena, Riverside and Barret, lying along an east-west line. Correlation of corresponding cycles of the surface waves shows changes in phase velocity between the respective stations that indicate that the earth's crust becomes thicker as one goes from the coast into the mountains. A somewhat similar study is being made in western Nevada by Evernden and Tocher of the University of California.

Marine refraction studies are being carried on in several widely separated oceanic areas. Prof. Ewing has just completed a cruise to the Mediterranean in which seismic refraction was used along with other tools such as magnetometers, bottom samplers, and fathometers. Sir Edward Bullard of Cambridge University

has just returned from a cruise to the mid-Atlantic Ridge, where magnetic and geothermal measurements were also made. Refraction was employed in several areas of the Pacific on a recent expedition from the Scripps Institute of Oceanography.

Mechanics of Faulting

During the past year, Prof. C. H. Dix of California Institute of Technology has embarked upon a fundamental study, using geophysical tools, of the mechanics of faulting. In one phase of this program Dr. Dix has been making gravity, seismic, and topographic measurements over a typical fault in San Bernardino County, California. His initial objective, namely to measure more accurately the

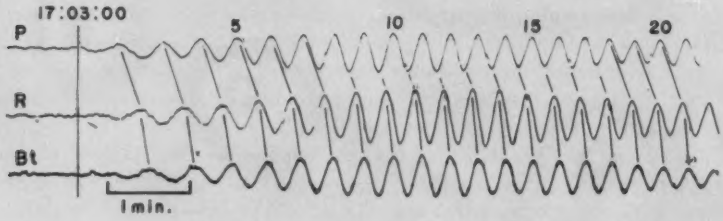

FIG. 11. Phase velocity variations in surface waves from earthquakes which indicate variations in crustal thickness. P is Pasadena; R is Riverside; Bt is Barrett. These stations are from 50 to 100 miles apart.

indicated horizontal displacement (about 4,000 feet) has had to be altered. The reason is that geophysical evidence indicates that the fault terminates at two points only 16,000 feet apart. A conclusion thus far reached is that before superficial indications of large horizontal displacements on faults are to be accepted, a study of the ends of the faults should be made and made a part of the whole picture. This is a problem which is of undeniable interest to petroleum geologists.

Paleomagnetism

An increasingly popular subject for geophysical research at universities and endowed institutions is paleomagnetism. About eight years ago, John Graham at the Carnegie Institution of Washington began a systematic program of measurements on the direction of magnetization of sedimentary rocks in place. He found that in most cases the direction was not the same as that of the earth's present field, but that it was usually displaced by 30° or so, and in some cases it

seemed to be completely reversed. Further investigation by Clegg and others at the University of London showed that late Paleozoic rocks in England had the magnetization that would be expected if the North magnetic pole lay in Eastern Siberia during their deposition instead of the Canadian Arctic, where it is now. This disclosure led to further measurements by Graham and his colleagues, this time on Permian rocks from the southwestern United States. These observations indicated that the North magnetic pole was somewhere in North Korea during the Permian. This essentially confirmed the conclusions reached by Clegg in Great Britain. On the basis of several lines of reasoning, one would expect the axis of the earth's rotation to shift with its magnetic axis. If this presumption is correct, the positions of the earth's geographic poles and equator should be established for all geologic periods by magnetic orientation measurements on a sufficiently large scale. Such data should give valuable information on climates and environments existing in various parts of the world during different periods of geologic time. This should be particularly interesting to the paleoecologist studying depositional environments. Fundamental principles of rock magnetization are being studied at Massachusetts Institute of Technology and at the University of California to aid in the interpretation of paleomagnetic observations. The work has obvious application to magnetic prospecting as well as to proposed techniques of core orientation by magnetic means.

CONCLUSIONS

The foregoing examples have been chosen to illustrate the interdependence that so often exists between academically sponsored geophysical studies and exploration geophysics. It is almost impossible to predict which of the geophysical studies now going on at non-commercial institutions may eventually lead to new or improved techniques of oil and mineral prospecting. This uncertainty is characteristic of all fundamental research. The potential benefits of such activity to the oil industry are so great, however, that the industry is giving an increasing amount of support to geophysical research projects at universities. This support may be of several kinds. Some oil companies are making direct research grants to universities; others are contributing equipment, facilities, and research fellowships. Large-scale cooperatively sponsored projects such as those at Massachusetts Institute of Technology and the University of California at Los Angeles represent a new type of approach which offers many benefits both to the participating companies and to the academic groups actually carrying on the research.

Within the past year the American Petroleum Institute has set up a special committee to recommend API research grants to universities for fundamental studies relating to geophysics. Shortly after its establishment, the committee called a conference of leading geophysicists from universities and asked them how the oil industry could best support fundamental research in geophysics. A second conference was held a year later in September, 1956. During its first

year the committee obtained API grants totaling $30,000 for five university groups. This financial support of fundamental geophysical research by the API will be increased to $60,000 for the year 1957–58. As another example of the oil industry's interest in these matters, a primary objective of the SEG Standing Committee on Research is to promote better liaison and understanding between exploration geophysicists and those engaged in fundamental geophysical research.

Both as a branch of technology and as a pure science, geophysics is one of the youngest of all technical fields. Its development as a tool for oil exploration has been rapid and its effectivness has made possible continued technological improvements. However, the point of diminishing returns seems finally to have been reached and the rate of oil discovery is no longer keeping pace with the cost of exploration. When this occurs, it is a warning that we need new fundamental principles and new ideas to serve as a basis for further technological development. *These principles and ideas are most likely to grow out of fundamental research in universities and similar institutions.* Thus the increased support the oil industry is giving such research may pay unexpectedly large dividends to the oil industry and through it to our entire oil-dependent economy.

ACKNOWLEDGMENT

The cooperation of innumerable oil companies, geophysical service companies, logging companies, and universities which have made technical data and statistical information available to the authors is gratefully acknowledged. The help of Dr. F. G. Blake, Jr. of California Research Corporation in collecting information for us from West Coast universities is particularly appreciated.

APPENDIX

DESCRIPTIVE LIST OF RESEARCH PROJECTS AT NON-COMMERCIAL INSTITUTIONS RELATING TO EXPLORATION GEOPHYSICS

The information in the following list was collected by the authors during August and September, 1956. Most of the material was obtained by correspondence with key personnel at the various institutions represented. Some of it was extracted from the minutes of the meeting of the American Petroleum Institute's Coordinating Committee on Geophysical Research held at Tulsa in September, 1956, while other portions were based on a report prepared for the authors by Dr. F. G. Blake, Jr.

In soliciting our information, no attempt was made to cover all of the institutions where geophysical research work is going on. In general, inquiries were addressed to the leaders of the larger research groups in the United States and Canada which were known to be working on aspects of geophysics pertinent to exploration. Outside of North America, only one group, the Department of Geodesy and Geophysics at Cambridge University, was contacted. More adequate coverage of geophysical work across the Atlantic is being left for next year's review paper.

Projects included in this list fall within the following categories:

1) Research on physical principles underlying present or prospective geophysical prospecting techniques.

2) Research on physical properties of earth materials having a bearing on geophysical exploration.

3) Geophysical surveys providing geological information on a regional or global scale that might conceivably be useful in exploring for petroleum or minerals.

It is hoped that this list will be useful to geophysical research workers in providing a brief but fairly comprehensive summary of current North American activity in their own and related fields of investigation.

EXPLORATION METHODS

Seismic Exploration

Elastic Properties of Rocks

1. *Seismic velocities of sea-bottom core samples:* Staff members at Lamont Geological Observatory, Columbia University, have been devising methods for measuring seismic velocities in unconsolidated ocean-bottom sediments brought up in cores.

2. *Elastic wave velocities in rock cores:* Francis Birch at Harvard University has been measuring compressional wave velocities in jacketed rock samples up to pressures of approximately 10,000 atmospheres.

3. *Laboratory measurement of seismic velocities in rocks:* Darrell Hughes, of the University of Texas, is measuring seismic velocities in granites, dunites, and gabbros at temperatures up to 300°C and pressures up to 10 kilobars. Dynamic pressure effects in metals and rocks are being studied by generating shock waves with plane wave fronts having pressures up to 600 kilobars.

4. *Velocity of seismic waves in sandstone:* A graduate student at the Colorado School of Mines has completed a series of measurements on seismic velocities in Ottawa sand under various pressures and degrees of fluid saturation.

Seismic Wave Propagation (General)

1. *Generation of sonic waves in a fluid cylinder:* T. W. Spencer and other graduate students working under C. H. Dix at California Institute of Technology have been studying the propagation of sonic waves generated in a fluid cylinder, a problem having important applications in acoustic logging.

2. *Two-dimensional seismic model studies:* Jack Oliver at Lamont Geological Observatory, Columbia University, has been studying the propagation of Rayleigh waves around corners by use of two-dimensional models. In general surface waves are both reflected from and transmitted around the corners but there is some conversion to body waves. These studies are being applied to the problem of what happens when a Rayleigh wave from a continental earthquake reaches the boundary between continent and ocean.

3. *Model seismology at St. Louis University:* Plans are under way for setting up seismic model experiments at St. Louis University to study various problems such as the effect of certain barriers on the propagation of surface waves.

4. *Model experiments on seismic surface waves:* B. F. Howell, Jr. of Penn State is planning to construct a seismic model to test various theories on the generation of surface waves. He would like to study the dependence of surface wave characteristics on reflecting interfaces within the low-velocity layer.

5. *Model seismology at Caltech:* Frank Press of the Seismological Laboratory at Caltech, has been carrying on seismic model experiments to study the effect of surface layering on the character of seismic signals and noise. Shear waves in a metal plate are being used to study the guided propagation of compressional waves in layered media.

6. *Fundamental seismic studies at Lamont:* Jack Oliver at Lamont Observatory, Columbia University, is supervising fundamental studies on surface wave dispersion, including higher modes; surface wave radiation patterns; fault plane orientation; energy release; and crustal thickness.

Scattering of Seismic Waves (theory and experiment)

1. *Scattering of seismic waves:* Leon Knopoff at the U. of California Institute of Geophysics, Los Angeles has been in charge of a group studying elastic wave scattering under the sponsorship of twelve oil companies. Small-scale seismic models are providing significant data on the reflection and diffraction of seismic waves at boundaries and discontinuities. Energy loss by propagation through a continuum of scatterers is being analyzed theoretically as is the waveform of seismic pulses diffracted into a "shadow zone."

2. *Effects of scattering layers in the ocean on sonic waves:* J. B. Hersey at Woods Hole Oceanographic Institution and his colleagues have observed returns on their echo sounders from "scattering layers" at middle depths in the ocean. These layers consist presumably of marine life. Recently increased resolution and improved techniques have made it possible to identify reflections from individual fish (?) from such layers. Applications to scattering of seismic waves in the earth may be indicated.

3. *Scattering experiments with models at D.T.M.:* In order to study the origin of noise on seismograms, H. E. Tatel of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has carried on model experiments which showed that this noise can be explained by surface and volume scattering, that at the surface being accompanied by the conversion of body to surface waves.

Generation of Seismic Waves by Explosions and Other Artificial Sources:

1. *Explosion-generated seismic waves:* Shell Oil Company has been supporting a long-term research program at St. Louis University for studying the generation and propagation of elastic waves from explosions in the ground. Some problems currently receiving attention are:

(a) Evaluation of methods for obtaining energy—frequency relationships from records of ground displacement.
(b) Determination of wave forms generated in limestone by small explosions both near the source and after reflection from a free surface.
(c) Generation of shear waves by blasts.
(d) Transmission of waves through a clay overburden overlying a thick limestone.

2. *Generation of seismic waves by explosives:* B. F. Howell, Jr. of Penn State has been supervising an experimental research program to learn how seismic pulses are created and transformed from one form to another in the ground. By evaluating the kinetic energy of the pulses, he has shown that the attenuation of seismic waves increases rapidly with depth, at least down to the base of weathering. Also, there appears to be an exponential increase of total seismic energy with depth of the shot.

Frequency analysis of seismic waves has been carried on with a photomechanical analyzer designed to give a nearly continuous spectrum of a transient pulse. An effort was made to distinguish surface from body waves on the basis of their frequency spectra.

3. *Non-explosive sources of seismic waves:* B. F. Howell, Jr. of Penn State has been studying the properties of seismic waves generated by the impact of a falling weight and also by a mechanical vibrator. Frequency content and attenuation of the body and surface waves thus generated are being measured.

4. *Generation and propagation of seismic waves from explosives:* A research program is being started at the University of Utah on the generation and propagation of seismic waves by explosives. One project involves a study of the percentage of the energy of the explosion going into the seismic wave as a function of the size of the cavity created by the explosion.

Improvement of Signal-to-Noise on Seismic Records

1. *Statistical analysis of seismograms:* Stephen M. Simpson, Jr., J. G. Bryan, and others at MIT are continuing their efforts to apply recently developed statistical theory to "the interpretation of otherwise hopeless exploration seismic recordings." Techniques using high speed computers have been developed to boost the appearance of reflections in the following cases:

(a) where the reflection is mixed with partially predictable noise of different properties from the reflection, or
(b) where the reflection follows a path across the record that obeys the laws of geometric optics and where the noise has no cross-correlation.

For the second case a computing procedure has been developed which produces a structural cross-section directly from the raw data. Methods of dealing with reflection overlap are also being studied.

A new theory of seismic wave propagation in statistically inhomogeneous media may lead to an extension of the geologic information obtainable from the seismogram.

2. *Non-constant element filter:* Theory for a non-constant element filter is being developed at MIT Such an instrument could be useful in extracting new and better information from seismic recordings.

Application of Echo-sounding to Prospecting

1. *Fathometer for sub-bottom reflections:* S. T. Knott and J. B. Hersey of Woods Hole Oceanographic Institution have modified conventional echo-sounding equipment to record reflections from formation tops below the water bottom in shallow water areas. The sub-bottom reflections are observed only when pings from a broad-spectrum sound source are recorded through a low-frequency filter.

2. *Use of Sonar on land for mineral prospecting:* The U. S. Geological Survey is doing experiments to adapt Sonar equipment and techniques for mineral exploration on land.

Seismic Exploration for Minerals

1. *Seismic methods of mineral exploration;* The U. S. Geological Survey has inaugurated a programme for investigating possible seismic and acoustic methods of exploration for minerals (other than hydrocarbons). This programme will involve a fundamental study of all pertinent aspects of seismic wave generation and propagation in the earth.

2. *Location of sources of mine noise:* Prof. L. O. Bacon of Michigan College of Mining and Technology is supervising a research project on locating sources of mine noise by micro-seismic measurements.

Gravity Exploration

Instrumental Development

1. *Gravity measurement at sea:* With the co-operation of Prof. Anton Graf, staff members of Lamont Geological Observatory are testing the applicability of a new gravity meter designed by Prof. Graf for use on ships at sea.

2. *Vibration gravimeter:* Reginald Gilbert has succeeded in making the vibration-frequency type gravity meter he developed at Cambridge University operate satisfactorily in the laboratory and is continuing his work on it at the Dominion Observatory in Ottawa. He believes that it may be particularly suitable for gravity measurements on ice.

3. *Gas gravimeter for use at sea:* George Woollard at the University of Wisconsin is modifying a Haalck gas gravimeter for use on surface vessels in making gravity observations at sea. Shallow water measurements are being made by water-bottom gravimeters in the Atlantic coastal area.

4. *New LaCoste gravimeter for measurements at sea:* U.C.L.A. (Institute of Geophysics) is sponsoring gravity observations at sea with a new LaCoste gravimeter designed for use aboard submarines. This instrument promises to simplify greatly the measurement of gravity over oceanic areas.

Earth Tides

1. *Tidal yielding of the earth:* U.C.L.A. (Institute of Geophysics) is obtaining data on the yielding of the earth from tidal forces by means of a special gravimeter designed by LaCoste and Clarkson. The differences in yielding at different places on the earth will be studied during the International Geophysical Year.

Magnetic Prospecting

Instrumental Development

1. *Magnetic measurements at sea:* In co-operation with Varian Associates, staff members of the Lamont Geological Observatory are testing a nuclear resonance magnetometer as a possible replacement for the flux-gate magnetometer in recording continuous magnetic profiles along the track of Lamont's research vessel *Vema.*

Electrical and Electromagnetic Prospecting

Electrical Properties of Rocks

1. *Physical properties of earth materials:* The U. S. Geological Survey is obtaining data on various physical properties of rocks, including their electrical resistivity, dielectric constant, magnetic susceptibility, remanent magnetization, thermal conductivity, and elastic and plastic behavior.

2. *Effects governing electrical constants:* A program to learn how resistivity, dielectric constant, and self-potential of rocks are controlled by other properties is under way at Penn State, with E. J. Moore in charge. Effects of pressure, wettability, moisture content, and chemical constituents dissolved in the contained water are being investigated.

3. *Resistivity of synthetic rock cores:* Experiments at the University of Utah on the resistivity of synthetic cores that resemble rocks show the effects of changing the percentage of lead or the fractional volume of saturating conductive fluid.

Induced Polarization Prospecting and Logging

1. *Induced polarization prospecting method:* Theodore Madden and graduate students at MIT have shown that the dependence of rock impedance upon frequency is very sensitive to the content of metallic minerals. A prospecting method based on this relation has been successfully tested in the field.

2. *Induced polarization well logging:* The U. S. Geological Survey is developing a system for logging by induced polarization equipment.

Resistivity Prospecting

1. *New resistivity prospecting method:* Theodore Madden of MIT is experimenting with a technique of resistivity prospecting in which apparent resistivities are recorded with multiple sender-multiple receiver apparatus. Semi-quantitative interpretation methods have been developed for a non-horizontally layered earth.

2. *Analogue computer for resistivity and induced polarization data:* The U. S. Geological Survey has designed an analogue computer for use in interpreting resistivity and induced polarization data. The computer is in effect a model which simulates the resistance and dielectric constant of a layered earth.

Electromagnetic and Magneto-telluric Methods

1. *Electromagnetic prospecting studies:* The U. S. Geological Survey is developing and evaluating electromagnetic methods for base-metal and disseminated-ore exploration. A variable-frequency type of equipment is being developed and an electromagnetic technique for measuring magnetic susceptibility in drill holes is being perfected.

2. *Magneto-telluric prospecting:* A method for investigating electrical properties at depth by the use of magneto-telluric measurements on the surface is being developed at MIT.

3. *Electromagnetic prospecting studies:* Under the supervision of L. B. Slichter at U.C.L.A., a graduate student is investigating phase changes that occur when electromagnetic waves encounter

bodies of moderate electrical conductivity such as certain ores. A model has been constructed and theoretical solutions for a layered earth are being obtained with the aid of an electronic computer.

4. *Electromagnetic oscillations:* Hugo Benioff and Frank Press at the Seismological Laboratory, Caltech, have been recording natural electromagnetic oscillations in the period range 0.2 to 100 seconds. A tripartite network of recording stations over Southern California shows that nearly sinusoidal disturbances are simultaneous in time and identical in form at the three stations. Applications to magneto-telluric prospecting may be possible.

5. *High-frequency fluctuations in the earth's magnetic field:* Prof. Holzer of U.C.L.A. (Institute of Geophysics) has been investigating natural fluctuations of the earth's magnetic field in the range from 1 to 1,000 cps. These fluctuations are important because they limit the sensitivity of several prospecting methods, such as the electromagnetic and magnetic. They also offer a possible means of studying geologic structures.

6. *Study of geologic structures with radio signals:* A study is in progress at the University of Utah for correlating intensity of radio signals in the Salt Lake Valley region with known geologic structure, especially along the Basin and Range faults.

Uranium Exploration

1. *Uranium exploration methods:* The U. S. Geological survey is engaged in a series of research projects on radioactivity that are sponsored by the U.S. Atomic Energy Commission. These include studies of scattering and absorption of gamma radiation by earth materials, radon contamination in drill holes, and isotope identification by means of a time-interval differentiator.

2. *Radioactivity propsecting:* At the University of Utah, the distribution of radon in spring and stream waters is being investigated as a possible indicator of uranium ores.

GEOLOGICAL STUDIES USING GEOPHYSICAL TOOLS

Determination of Regional and Crustal Structure on Land

Seismic Investigations

1. *Seismic studies at University of Wisconsin:* George Woollard at the University of Wisconsin reports seismic measurements to study stratigraphic structure or crustal structure of the following kinds: Land measurements on the Atlantic coastal plain and in the glacial drift areas of Wisconsin, deep crustal studies in the midcontinent and Rocky Mountain regions, and marine measurements over the Atlantic Shelf and in the Great Lakes.

2. *Seismic crustal studies in Utah:* The Colorado School of Mines is planning some seismic recordings in Utah to check on the unexpectedly small crustal thickness deduced for this area from the seismic measurements of Tuve and Tatel in the southern part of the Colorado Plateau.

3. *Crustal studies in California:* Joshua L. Soske of Stanford University has been conducting a refraction survey over a 90-mile profile between Elwood and Monolith, California to determine the structure of the earth's crust in this area. Quarry blasts and pier demolitions served as energy sources. Large events that may be refractions or reflections from the base of the crust were observed on his records at 17 or 18 seconds.

4. *Crustal thickness determination from phase velocities:* Frank Press of the Seismological Laboratory, Caltech has demonstrated a new technique for determining crustal thickness by the dispersion of earthquake surface waves. He has observed the phase velocities directly by correlating corresponding cycles on earthquake records made at various stations which are relatively close together along a line with the epicenter. Changes in phase velocity along this profile indicate a change in the thickness or composition of the crust or in both. Two-dimensional model experiments have been carried on in connection with this study.

5. *Crustal layering in central North America:* St. Louis University has installed new high-magnification, short-period seismographs to record earthquakes from the New Madrid area of Missouri more accurately. Data thus obtained should give more accurate information on velocities and thicknesses of crustal layers in central North America.

6. *Crustal thickness from earthquake surface waves:* J. F. Evernden and Don Tocher of the University of California have set up a tripartite net of earthquake recording stations in western Nevada to observe the dispersion of surface waves in this area. The thickness of the earth's crust can be computed from the data which this net is expected to record whenever a large earthquake occurs in the South Pacific.

Gravity and Magnetic Investigations

1. *Regional geophysical studies in Colorado Plateau:* Aeromagnetic and regional gravity coverage is being obtained by the U. S. Geological Survey in the Colorado Plateau area to define important regional structural trends, depths to basement, and buried intrusive bodies.

2. *Regional geophysical studies in Lake Superior area:* Aeromagnetic, gravity, and rock sampling studies are being undertaken by the U. S. Geological Survey in the Lake Superior area with the object of learning how ferromagnetic minerals can be identified from the aeromagnetic anomalies they yield.

3. *Regional geophysical studies in Eastern Missouri:* Deep-seated structures in the eastern Ozark region are being investigated by detailed magnetic and gravity surveys carried out by students at St. Louis University. Susceptibility of sedimentary rocks in this area is being measured in the University laboratories to determine whether any of the observed magnetic anomalies are actually sedimentary in origin.

4. *Gravity surveys in Nevada and California:* George A. Thompson of Stanford University and his students have been running gravity profiles in Central Nevada for a regional structure study. They have also run lines across San Francisco Bay on the bridges and find a very large positive anomaly over the Bay.

5. *Regional gravity and magnetic program in Colorado:* At the Colorado School of Mines, a residual gravity map of Colorado is being completed and the gravity data are being correlated with regional geology and magnetic data. Data from 3,400 stations are being incorporated into the analysis. Observations at nearly 2,200 of the stations were made by Mines students or staff members. A magnetic survey was made on the eastern edge of the Front Range to trace the thrust fault in the neighborhood of Golden and Morrison.

6. *Regional gravity and magnetic map of Utah:* At the University of Utah, Kenneth L. Cook is preparing a regional gravity and magnetic map of Utah. Isostatic studies are being made of the Uinta Mountains to ascertain if they have roots.

Other Studies

1. *Structural studies of Canadian Shield:* J. Tuzo Wilson of the University of Toronto is studying the structure of the Canadian Shield by use of aerial photographs, radioactive age determinations, and published geology. The results of this study will be applied to the problem of how continents develop.

Determination of Regional and Crustal Structure at Sea

Seismic Investigations

1. *Seismic study of English Channel:* M. N. Hill of Cambridge University and his colleagues have completed a program of refraction measurements near the mouth of the English Channel and the results have just been published in the *Quarterly Journal of the Geological Society of London.*

2. *Seismic investigation of mid-Atlantic Ridge:* M. N. Hill of Cambridge University has carried on recent refraction seismic measurements in deep portions of the eastern Atlantic Ocean and over the mid-Atlantic Ridge.

3. *Refraction surveys in Pacific Ocean:* The Scripps Institute of Oceanography, La Jolla, California has sponsored a refraction survey in the Pacific to determine crustal and sedimentary thicknesses in the continental borderland of southern California, the Aleutian Ridge, the Bering Sea and the western Hawaiian Islands. This survey was under the direction of George Shor.

4. *Regional geophysical study of the Caribbean area:* Charles B. Officer of Rice Institute reports on a broad geophysical study of the Caribbean Sea, the Lesser Antilles, and the Puerto Rican Trench. Seismic data obtained in this area by Dr. Officer on a Woods Hole-sponsored cruise are being analyzed. Particular emphasis is being placed on lithologic identification of the materials with different seismic velocities.

Gravity Investigations

1. *Gravity measurements at sea:* J. C. Harrison of Cambridge University has obtained gravity data in a submarine which circumnavigated the continent of Africa. The Red Sea shows a narrow positive anomaly down its axis while the Gulf of Suez and the Gulf of Aqaba have negative anomalies similar to those of the African rifts.

Magnetic Investigations

1. *Magnetic study of mid-Atlantic Ridge:* A nuclear resonance magnetometer was towed behind the Research Ship *Discovery II* during a recent expedition to the mid-Atlantic Ridge sponsored by Cambridge University. According to Sir Edward Bullard, leader of the expedition, large anomalies were observed over the ridge. In the plain to the east the magnetic anomalies were smaller but were still much more substantial than would have been expected on the basis of the flat bottom topography.

2. *Magnetic observations in the Mediterranean Sea:* Magnetic profiles taken by Maurice Ewing and his associates on the Lamont Geological Observatory cruise in the Mediterranean Sea during the summer of 1956 show a very uniform field in the Eastern portion of the Sea over an area of rugged bottom topography.

Studies Using a Combination of Methods

1. *Geophysical studies in the Mediterranean:* Lamont Geological Observatory, Columbia University, sponsored a cruise last summer to the Mediterranean Sea for studying bottom topography, sediments, water circulation, magnetic fields, and crustal structure. Results will be compared with those previously obtained by Ewing and his associates in the Caribbean and the Gulf of Mexico.

Geodetic Studies

1. *Worldwide gravity network: connections between base stations:* B. C. Browne of Cambridge University has been establishing long-distance connections between national gravity base-stations using pendulums. This program has coordinated gravity data between England, Canada, the United States, Alaska, South Africa, and Norway. An extension of this work to South America and the Antarctic is contemplated in the near future.

2. *Regional and global gravity program at University of Wisconsin:* The program of gravity measurement being led by George Woollard at the University of Wisconsin includes:

a) the establishment of an international gravity reference standard;
b) the establishment of a world network of gravity bases for integrating all data into a common net;
c) regional gravity measurements in North America for studying regional geology and crustal structure;
d) preparation of a "reasonably complete" gravity map of the United States.

Studies of the Mechanics of Faulting

1. *Fault studies with geophysical tools:* C. H. Dix of California Institute of Technology and his students are studying the mechanics of faulting in general by geophysical measurements in the field over selected faults. Last summer he and his students obtained gravity readings and topographic data over a fault in San Bernardino County, California. Seismic refraction, magnetic, and resistivity measurements are planned for the current school term.

2. *Mechanics of faulting:* Alan Sanford, a student of C. H. Dix at California Institute of Technology, is carrying out theoretical and model studies of the processes by which vertical basement displacements generate faulting in the overlying sediments. He is comparing his results with field observations over a fault believed to have originated in this manner.

3. *Faulting direction from earthquake shear waves:* St. Louis University seismologists have developed a method for determining the direction of earthquake-producing fault movements from the shear waves recorded at distant seismograph stations.

4. *Energy of earthquakes and nature of associated faulting:* Perry Byerly of the University of California at Berkeley has developed techniques for computing the energy in an earthquake, the depth of the fault break causing it, and the attitude of the fault from seismograms obtained at distant stations

Geothermals

1. *Geothermal studies at Harvard:* Heat flow through the earth's crust is being investigated by a group working under Francis Birch at Harvard. Data from California, West Texas and New Mexico, and Eniwetok Atoll are being used in this study.

2. *Heat flow in mid-Atlantic Ridge:* Sir Edward Bullard of Cambridge University has measured heat flow in the bottom sediments of the mid-Atlantic ridge and has observed a flow of 6×10^{-6} cal/cm^2-sec, a value much greater than any observed previously anywhere on the earth.

Rock Formation and Deformation

1. *Rock deformation under high pressures:* David Griggs of the University of California Institute of Geophysics is continuing his studies of the deformation of rocks and rock minerals and has recently produced new equipment for imposing prescribed rates of shear strain upon his specimens.

2. *Chemistry of rock formation:* A large program is going on at Penn State to learn what are the conditions of temperature and pressure in which different mineral species are in equilibrium. In addition to minerals forming at high temperatures, the group is interested in the formation of those clay minerals which are common in sedimentary rocks.

3. *Sedimentation rate measurement by radioactivity:* Patrick M. Hurley of MIT is endeavouring to measure the rate of sedimentation in ocean bottom cores by determining the relationships of the radioactive elements that are out of equilibrium.

Paleomagnetism

1. *Paleomagnetism studies at Berkeley:* Jean Verhoogen at the University of California in Berkeley is measuring direction of magnetization in sediments and lavas from California and adjacent states. One object is to compare directions in sediments and the lavas interbedded in them. Another is to determine reliable positions for the magnetic poles in the early Tertiary. Another aspect of this work is a fundamental study of how rocks acquire permanent magnetization and how reversals in direction of magnetization can occur. "Crystallization magnetization" is receiving particular attention:

2. *Genesis of magnetic minerals in sedimentary rocks:* Richard R. Doell of MIT and several of his graduate students are studying the origin and significance of remanent magnetism in sedimentary rocks. A better understanding of the genesis of the minerals causing this magnetism should lead to a useful classification of sedimentary rock types. Measurements on oriented rock samples of various magnetic properties should cast important light on indicated wandering of the magnetic pole during

Mesozoic and earlier times. They may also be useful in solving certain problems of structural delineation.

3. *Paleomagnetism studies at the D.T.M.:* John W. Graham of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been continuing his program of measuring the direction of magnetization in sedimentary rocks. A study of Triassic and Permian sediments from Maryland, New Mexico, Arizona, and Utah has shown that the earth's field in the Triassic was approximately the same in direction as that today but that the Permian sediments show a consistent direction of magnetization far different from that of the present field. The results for the Permian agree with measurements made on late Paleozoic sediments in England. Thus there is evidence that the earth's north magnetic pole, and by inference its north rotational pole also, were in the vicinity of Korea during the Permian.

Age Determination and Dating of Rock

1 *Sedimentary age-determination:* Patrick M. Hurley of MIT is developing a method of dating sediments containing glauconite by measuring strontium/rubidium and argon/potassium ratios.

2. *Age determinations at Berkeley:* A program of dating sedimentary rocks by the potassium-argon method is under way at the University of California in Berkeley. One purpose of this work is to establish the time involved in the emplacement of the Sierra Nevada batholith and its subsequent uplift, denudation, and subsidence. Another is to establish dates for Tertiary epochs and stages and for well-established Tertiary stratigraphic zones in the Great Valley of California and in the Gulf Coast region.

3. *Age of galenas:* R. D. Russell and R. M. Farquhar of the University of Toronto are studying the isotopic composition of lead ores so as to determine their age and origin. It is hoped that this research will make it possible to date galenas as readily as uranium ores.

4. *Age determination at D.T.M.:* A group at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington working under L. T. Aldrich has been evaluating various methods of mineral age determination using different naturally occurring radioactive elements. This work has indicated the ranges of reliability of the different methods for various kinds of rocks.

Glacial Studies

1. *Glacial studies with geophysical tools:* A party of eleven men from the University of Toronto spent the summer of 1956 making seismic and gravity observations on glaciers in British Columbia. The purpose of the expedition was to train men and test equipment for work in the arctic during the I.G.Y.

2. *Glacial map of Canada:* A committee consisting of Wilson at the University of Toronto, Mathews of the University of British Columbia, and Prest of the Geological Survey of Canada is compiling a new glacial map of Canada on the basis of aerial photographs and other information.

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REPORT OF SEG SUBCOMMITTEE ON INFORMATION ON MAGNETIC RECORDER CHARACTERISTICS*

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Information on geophysical magnetic recording and play back systems has been obtained from specifications furnished by the several manufacturers. As will be seen in the following summary, the various systems differ in basic design features to such a degree that it is difficult to anticipate the achievement of any large-scale standardization. This information is presented as being of interest to those concerned with the handling of seismic data, but with no intention of suggestion or recommendation.

RECORDER CHARACTERISTICS

The geophysical recorders can be grouped according to their method of recording, and their method of transporting the magnetic tape past the recording heads. The Ampex 700, the Southwestern Industrial Electronics MR-4 and MR-5, the Electrodynamic Instrument Corporation FMR-30, and the Texas Division of Brush Electronics Company TR-2 uses frequency modulation and a drum transport; the Houston Technical Laboratories magnedisc system uses frequency modulation and a rotating disc as the transport medium. The Electro-Technical Laboratories use pulse-width modulation, with a drum transport for their FR-1 system, and a continuous reel of tape for their DS-2 system. The S.I.E. PMR-6, the Electrodynamic Instrument Corporation DR-30, and the Techno Instrument Company TI-400A and TI-450 systems use direct recording with a-c bias, and drum transports. The transport characteristics and the recording characteristics of the various systems are listed in Tables 1 and 2.

The presentation of the performance characteristics of the various systems must be prefaced with a discussion concerning the terms used, since a considerable uncertainty of the exact meanings exists at the present time. The figure for the harmonic distortion, as generally given, does not indicate which distortion components have been considered; also, even where all the distortion components have been examined, it is not clear whether the figure is for the sum of the components or is the rms value.

The situation for the signal-to-noise ratio of the record-playback systems is somewhat more complicated. For carrier-type systems, i.e., frequency modulated or pulse-width modulated, the signal-to-noise ratio is the ratio between a measure of the output due to a fully modulated signal and a measure of the output due to a zero modulated signal. The measure may be rms-to-rms or peak-to-peak, and

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TABLE 1. TRANSPORT CHARACTERISTICS

	Transport	Drive Motor	Coupling	Transport Speed	Size of Medium	Record Time
Ampex 700	12¾-in. drum	Fork-controlled synchronous	Belt to friction rim drive	7½ in./sec	4 in.×40½ in.	5 sec
Electro-Tech DS-2 & DM-3	Reel	Fork-controlled synchronous	Belt to roller drive	12–20 in./sec	4-in. reel	Unlimited
Electro-Tech FR-1	14½-in. drum	Fork-controlled synchronous	Gears	7½ in./sec	2¼ in.×45 in.	5½ sec
Electrodynamic FMR-30	7.17-in. drum	Fork-controlled synchronous with inertia damping	Gears	3¾ in./sec	6 in.×22½ in.	6 sec
Electrodynamic DR-30	7.17-in. drum	Fork-controlled synchronous with inertia damping	Gears	3¾ in./sec.	6 in.×22½ in.	6 sec
H.T.L. Magnedisc	Disc	d-c with servocontrol	Gears	Disc rotates at 10.9 rpm	18¼-in. diameter disc	5 sec
S.I.E. MR-4	14-in. drum	Fork-controlled synchronous with servosystem	Two-stage friction rim drive	7½ in./sec	4 in.×45$\frac{5}{16}$ in.	5½ sec
S.I.E. MR-5	14-in. drum	Fork-controlled synchronous with servosystem	Two-stage friction rim drive	3¾ or 7½ in./sec	4 in.×45$\frac{5}{16}$ in.	11 or 5½ sec
S.I.E. PMR-6	14-in. drum	Fork-controlled synchronous	Gears	3¾ or 7½ in./sec	4 in.×45¼ in.	11 or 5½ sec
Techno TI-400A	7½-in. drum	Fork-controlled synchronous	Gears	3¾ in./sec	12 in.×24 in.	6 sec
Techno TI-450	7½-in. drum	Fork-controlled synchronous	Gears	3¾ in./sec	6 in.×24 in.	6 sec
Texas-Brush TR-2	14-in. drum	Fork-controlled synchronous with servosystem	Two-stage steel belt	7½ in./sec	4 in.×45$\frac{5}{16}$ in.	5.8 sec

TABLE 2. RECORDING CHARACTERISTICS

	Modulation	Number of Tracks	Width of Tracks	Separation of Tracks	Full Modulation Input (rms)	Full Modulation Output (rms)
Ampex 700	FM—2,700 cps, 40% maximum deviation	26	.050 in.	.075 in.	1 volt at 100,000 ohms	1 volt at 1,000 ohms
Electro-Tech DS-2 & DM-3	PWM—1,600 cps, 80% maximum variation in width	28	.050 in.	.125 in.	1 volt at 10,000 ohms	1 volt at 12,000 ohms
Electro-Tech FR-1	PWM—800 cps, 50% maximum variation in width	30	.040 in.	.0625 in.	1.0 microvolt at 200 ohms	———
Electrodynamic FMR-30	FM—2,250 cps, 65% maximum deviation	30	.050 in.	.1875 in.	0.5 volt at 1 megohm	1 volt at 20,000 ohms
Electrodynamic DR-30	Direct—with a-c bias of 5,000 cps	30	.050 in.	.1875 in.	0.25 volt at 1 megohm	0.01 volt at 125 ohms
H.T.L. Magnedisc	FM—4,000 cps, 50% maximum deviation	65-115	.050 in.	.070 in.	0.25 volt at 0.25 megohm	0.07 volt at 2,200 ohms 0.002 volt at 1,000 ohms
S.I.E. MR-4	FM—4,000 cps, 75% maximum deviation	28	.090 in.	.125 in.	1 volt at 0.5 megohm	1 volt at 2,000 ohms
S.I.E. MR-5	FM—4,000 cps, 75% maximum deviation	56	.090 in.	.125 in.	1 volt at 0.5 megohm	1 volt at 2,000 ohms
S.I.E. PMR-6	Direct—with a-c bias of 15,000 cps	28	.090 in.	.125 in.	———	———
Techno TI-400A	Direct—with a-c bias of 15,900 cps	50	.150 in.	.250 in.	0.2 volt at 60 ohms	0.2 volt at 500 ohms
Techno TI-450	Direct—with a-c bias of 15,000 cps	26	.150 in.	.250 in.	0.2 volt at 60 ohms	0.2 volt at 500 ohms
Texas-Brush TR-2	FM—4,000 cps, 50% maximum deviation	28	.090 in.	.125 in.	0.5 microvolt at 250 ohms	1 volt at 1,000 ohms

in the case of the latter, it is not clear whether there has been an elimination of the less frequently occurring high peaks, or what arbitary criteria for the measurement of the peaks have been applied. The rms-to-rms ratio is generally a more favorable appearing ratio than is the peak-to-peak by about 3–6 db. For systems using direct modulation with a-c bias, the noise observed when playing back from an unmagnetized tape is that due to irregularities of the magnetic medium which become apparent only when the medium is magnetized, and which vary with the intensity of magnetization.

Table 3 lists some of the performance characteristics of the several systems and indicates, where available, the conditions of the data. The Subcommittee on Definitions and Measurements Procedures is presently preparing a report which, if accepted by the various manufacturers, will undoubtedly cause numerous changes in Table 3.

FIELD RECORDER SPECIFICATIONS

The following paragraphs present additional characteristics which cannot be easily arranged in tabular form.

The Ampex 700 has no signal monitoring equipment but does contain a full set of demodulators so that simultaneous playback of all signal channels into a multichannel recorder is possible. A set of movable heads is optional so that fixed time shifts between channels of up to ±100 milliseconds can be inserted before playback. The total weight of the record-playback system is 242 pounds, and the volume is 10.9 cubic feet.

The Electro-Tech DS-2, DM-3 system uses 300-foot reels of tape and has a footage counter to locate specific portions. A scanning mechanism is provided so that any 4-second recording can be repeatedly played back through a full set of demodulators and displayed on an oscilloscope screen. The heads are fixed so that time shifting between tracks is not possible. The 28-channel system weighs 110 pounds, and the volume is 4.2 cubic feet.

The Electro-Tech FR-1 system incorporates a high gain amplifier with AGC and suppression with its modulators so that the geophone outputs are fed directly. A single demodulator with filtering, AGC, and suppression is available for field monitoring. Display is accomplished by automatically playing back the recorded signals, one at a time, into a teledeltos paper recorder mounted on a drum which turns in unison with the tape drum. In addition, a two-track visual monitor is available for monitoring any tracks during recording, two at a time. The system weighs 325 pounds.

The Electrodynamic FMR-30 is a drum type FM recording system which uses a full set of demodulators for simultaneous playback of all channels into a camera unit for a monitor record. It has adjustable magnetic heads for entering fixed corrections up to ±100 milliseconds during playback. A sealed high precision gear drive is used with a high inertia wheel being provided to damp out gear tooth noise. The total weight of the record-playback system is 187 pounds,

TABLE 3. PERFORMANCE CHARACTERISTICS

	Limit of Harmonic Distortion at Full Modulation	Signal-to-Noise Ratio	Time Alignment between Tracks	Timing Accuracy	Power (12 Volts)
Ampex 700	1% total	50 db peak-to-peak, 20–300 cps 45 db peak-to-peak, 1½–20 cps	1.0 ms	—	35A recording 42A playback
Electro-Tech DS-2 & DM-3	1.5%	44 db peak-to-peak, 5–300 cps	1.0 ms	1.0 ms	25A standby 40A recording 25A playback
Electro-Tech FR-1	1%	46 db peak-to-peak, 7–220 cps	0.5 ms	0.5 ms	21A standby 45A recording
Electrodynamic FMR-30	1% total	46 db rms-to-rms, 3–300 cps	1.0 ms	1.0 ms	15A standby 32A recording
Electrodynamic DR-30	3%	50 db rms-to-rms in absence of signal, 20–500 cps	1.0 ms	1.0 ms	15A
H.T.L. Magnedisc	0.75%	46 db peak-to-peak, 10–300 cps	0.25 ms	0.5 ms	15A recording 15A playback
S.I.E. MR-4	1% total	46 db peak-to-peak, 1–500 cps 60 db rms-to-rms with noise cancelling 20–100 cps	0.25 ms	0.25 ms	25A standby 47A recording
S.I.E. MR-5	1% total	Same as MR-4	0.25 ms	0.25 ms	25A standby 47A recording
S.I.E. PMR-6	3%	46 db rms-to-rms in absence of signal, 20–200 cps (30–36 db at peak modulation magnetization)	0.5 ms	0.5 ms	0.5A standby 10A recording
Techno TI-400A	2.5%	50 db rms-to-rms, 20–500 cps	1.0 ms	1.0 ms	18A recording 32A playback
Techno TI-450	2.5%	50 db rms-to-rms, 20–500 cps	1.0 ms	1.0 ms	18A recording 24A playback
Texas-Brush TR-2	1% total	54 db rms-to-rms, 5–500 cps 60 db rms-to-rms, 5–500 cps with noise cancelling	0.5 ms	0.5 ms	20A standby 60A record

and the volume is 5 cubic feet. Electrodynamics also manufactures a direct recording system designated the DR-30. It is essentially identical to the FMR-30 except for the recording method used. Its weight is 122 pounds with a volume of 2.7 cubic feet.

The H.T.L. magnedisc system uses a disc form for the recording medium. The equipment includes a full set of demodulators and field monitoring is accomplished by simultaneously playing back all the tracks into a camera unit. The total weight of the system is 282 pounds.

The S.I.E. MR-4 system includes a complete set of demodulators so that simultaneous playback of all tracks into the camera unit is possible. A direct viewer presenting the track images on a ground glass screen by means of a bank of galvanometers, or on a rotating long-persistence fluorescent screen is available. Individually movable heads over a range of ± 200 milliseconds are also available. The system weighs 440 pounds and the volume is 8.3 cubic feet.

The S.I.E. MR-5 is a dual-drum system with the same optional features regarding the monitoring or the movable heads as the MR-4. The dual drum permits the reprocessing of the data with the insertion of fixed time corrections as well as certain types of compositing or mixing. A third drum for photographic reproduction is also optional.

The S.I.E. PMR-6 is a portable system available with either frequency modulation or with direct modulation with a-c bias. Movable heads over a range of ± 100 milliseconds are optional. With direct recording the tracks are played back into the seismic camera for display; with FM recording no monitoring is normally available. Tapes are interchangeable with those of the MR-4 or MR-5 systems. The PMR-6 transport system weighs 43 pounds and its volume is about 1.5 cubic feet.

The Techno TI-400A system includes a full set of frequency and phase corrected amplifiers so that simultaneous playback into a camera unit is possible. Movable heads with a range of ± 90 milliseconds are normally provided. The system weighs 333 pounds complete (24 channels).

The Techno TI-450 is a hand-portable system with all components packaged in units no heavier than 54 pounds. The total weight of the drum assembly unit, power unit, and booster amplifier unit is 143 pounds.

The Texas-Brush TR-2 system incorporates a high gain amplifier with AGC and filtering with each modulator. A single demodulator for automatically controlled sequential playback into a teledeltos paper recorder is used for monitoring. The drum for the teledeltos paper rotates in unison with the tape drum. A direct viewer, using galvanometer-type displays on a ground glass screen is also available for simultaneous monitoring of all signal channels. The TR-2 weighs 350 pounds and its volume is 14 cubic feet.

The Texas-Brush TR-2 system is an improved system based on experience with a previous unit. It is gratifying to note that the new design has made its tapes interchangeable with those of a competitor's system so that a degree of

standardization has peen achieved. A new feature is that provision for sequential monitoring of any four of the tracks can be programmed so that a more rapid sampling type of monitoring is possible.

OFFICE PLAYBACK EQUIPMENT

The systems considered so far serve to obtain field recordings. Those which do not contain full sets of playback units will, of course, require such full sets in the office equipment in order to be able to simultaneously play back all the data tracks. This provision is necessary at some stage, presumably, even if the data are sequentially fed to other devices for further handling. The requirements for data handling as an aid to record interpretation, however, are more demanding than simple recording and playback. The movable heads available with some of the recording systems, which allow for rerecording the data with a fixed time shift between channels, and the dual drum of one of the field recorders have already been discussed. Other features, and the types of instrumentation presently available, are the following.

The Electro-Tech MT-4 playback system is intended as an adjunct to the FR-1 recording system. The MT-4 system has seven drums; five for magnetic tape operations are mounted on the same shaft, and two for visual display are connected to the tape drum shaft through a gear box. Four of the magnetic tape drums will accept the tape used in the FR-1, so that compositing or mixing of data from up to four records can be accomplished; the fifth tape drum has a single recorder head which therefore accepts data sequentially. The latter has provision for the introduction of fixed time corrections and for program control so that, for an assumed constant seismic velocity, the correction for variable normal move out can also be made. Correction for a velocity which varies with depth is not yet incorporated. Provision for transferring data between the five tape drums is also included. One display drum is for teledeltos recording of the time breaks, and the other is the main oscillograph; their speed of rotation relative to the tape drums can be varied and a portion of the recorded data can be spread out over the 45-inch length of the record. The main oscillograph drum has a print-head carrier whose position can be continuously varied so that up to 250 traces with one-sixteenth-inch spacing can be accommodated sequentially.

The Houston Technical Laboratories Seismac (seismic magnetic automatic computer) is a special purpose system for making fixed corrections and normal move-out corrections, including provisions for taking account of the variation of seismic velocity with depth. The variable velocity control is accomplished by switching heads on two multiple-head delay drums, the switching program being controlled by means of a photoelectric paper tape reader using a previously prepared punched-paper tape. The control is step-wise rather than continuous, with a 20-point approximation to the actual velocity curve. The Seismac is a single channel system, and the data tracks are processed sequentially.

The H.T.L. magnefilter (seismic time domain filter system) is an analog device

designed for general filtering applications by means of the cross-correlation technique. It contains a drum coated with the magnetic material, a single recording head, 18 playback heads arranged around the drum, each with its own gain control, and a summing amplifier. Sequential correlations of the successive input signals with a simulated filter characteristic (phase- and amplitude-adjustable) is obtained. The filter operator length is 45 milliseconds with sampling points at 2.5-millisecond intervals.

The Techno TI-450 is an automatic time corrector attachment for the Techno record-reproduce system which permits the reproduction of the originally recorded data with fixed corrections and with corrections for normal move-out. Fixed corrections over a range of ± 25 milliseconds and variable corrections for normal move out or seismic velocity variation up to 150 milliseconds with a maximum rate of correction up to 500 milliseconds per second, can be obtained. The variable correction is controlled by a cam assembly, the cam being prefabricated to fit the maximum spread length anticipated for the area under study and the velocity characteristics existing therein. Independent spread length controls are provided for each half of the spread, which may be either symmetrical or asymmetrical in form.

The Texas-Brush record processing equipment permits the insertion of fixed corrections and of variable corrections for move out or seismic velocity variations. Since it contains three magnetic tape drums rotating in unison, a large number of types of compositing or of mixing of data can be accomplished by multiple-re-recording. The initial record is transferred, track-by-track, from the first to the second drum with the fixed and variable time corrections inserted. Compositing or mixing of the records on the first and second drums to the third drum is also sequential, while the playback of the recordings of any drum into a multichannel recorder is a simultaneous process for all the tracks. During the time correction process, a special "memory wheel" process is used which maintains the low noise and distortion properties. The corrected tape can be played back into a constant speed camera on a corrected time basis (all channels simultaneously) or into a variable speed camera on a corrected depth basis (all channels simultaneously). The variable speed time-to-depth conversion camera, complete with a velocity function generator, is a standard part of this MRA-2 Magnetic Record Analyzer system.

DEPARTMENTS

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,766,421. J. R. Wait, H. O. Seigel, L. S. Collett, W. E. Bell, and A. A. Brant. Iss. 10/9/56. App. 2/26/52. Assign. Newmont Mining Corp.

Method and Apparatus for Geophysical Exploration. An electrical prospecting system for locating regions of mineralization in which a sinusoidal current is passed through the ground and also through a reference network of resistance and capacity which are adjusted so that the voltage drop is the same as that across two ground pick-up electrodes, the change in the balancing resistance and capacity with change in frequency being observed.

U. S. No. 2,766,422. S. Carbonetto. Iss. 10/9/56. App. 7/2/49 and 7/28/51.

Methods and Arrangements for Detecting Layers of Hydrocarbons in the Ground. A system for detecting buried hydrocarbons by radiowave reflection having an antenna with a vertical and two inclined branches in a shallow well and using an amplitude-modulated wave whose reflection is compared with the transmitted wave.

U. S. No. 2,769,956. A. A. Brant. Iss. 11/6/56. App. 10/4/54. Assign. Newmont Mining Corp.

Method and Apparatus for Determining the Azimuth and Dip of Sulphide Deposits. A method of locating sulphide ore bodies from a neighboring borehole by passing a current between ground electrodes on each side of the hole and measuring after the current is shut off the potential between a distant electrode and an electrode contacting the borehole wall and moved to various depths in the hole.

GEOCHEMICAL PROSPECTING

U. S. No. 2,761,975. P. B. Weisz. Iss. 9/4/56. App. 12/12/51. Assign. Socony Mobil Oil Co., Inc.

Method and Apparatus for Detecting Hydrocarbons. A method of gas analysis in which the gas is subjected to bombardment with electrons of specific energy and measuring the ionization current to obtain indication of components having ionization potentials equal to or less than the electron energy.

U. S. No. 2,767,320. N. D. Coggeshall and W. E. Hanson. Iss. 10/16/56. App. 11/24/52. Assign Gulf Research & Development Co.

Method of Geochemical Prospecting. A method of geochemical prospecting in which brine samples are taken from "dry" holes and analyzed for aromatic hydrocarbons, particularly benzene, and the concentrations plotted on a map in order to locate nearby petroleum accumulations.

MAGNETIC PROSPECTING

U. S. No. 2,770,774. H. B. Riblet. Iss. 11/13/56. App. 5/10/44. Assign. U. S. A.

Balanced Magnetometer. A flux-valve type of magnetic detector having a pair of identical high-permeability cores with windings connected in series to a center-tapped transformer with the junction of the two windings and the transformer center tap connected to a detector-amplifier.

U. S. No. 2,772,391. R. C. Mackey. Iss. 11/27/56. App. 8/18/54. Assign. The Regents of the University of Calif.

† Gulf Oil Corporation, Patent Department.

Recording Magnetometric Apparatus of the Nuclear-Resonance Type. A nuclear-resonance magnetometer having a modulating field superimposed on the field to be measured and employing a variable-frequency oscillator which is adjusted by a two-phase servo motor, one phase of the motor being excited by the modulating frequency and the other phase by the magnetometer output so that the oscillator is automatically tuned to the nuclear resonance frequency of the sample in the field to be measured.

(See also Patent 2,776,426 listed under WELL LOGGING.)

RADIOACTIVITY PROSPECTING

U. S. No. 2,764,695. W. C. Porter and W. E. Ramsey. Iss. 9/25/56. App. 8/14/53. Assign. U. S. A.

Geiger-Muller Counter Circuits. A G-M counter circuit which reduces the dead time of the counter by employing regenerative feedback between a discharge-limiting means and an amplifier tube.

U. S. No. 2,765,411. P. F. Kerr. Iss. 10/2/56. App. 2/24/53. Assign. Texaco Development Corp.

Detection and Measurement of Penetrative Radiation. A radioactivity detector using a phosphor which converts the radiation into light of a spectral band which is filtered and strikes a second phosphor which converts the light to another spectral band, the filter reflecting light of the second band so as to return it to the output and to a photomultiplier.

U.S. No. 2,765,418. P. B. Weisz. Iss. 10/2/56. App. 9/30/52. Assign. Socony Mobil Oil Co., Inc.

Geiger-Muller Counter Tube. A G-M tube whose internal atmosphere has hydrogen and saturated hydrocarbons and having in the envelope a metal catalyst for catalyzing the hydrogenation of any unsaturated hydrocarbons which may be present.

U. S. No. 2,767,324. R. J. Van de Graaff. Iss. 10/16/56. App. 6/26/53. Assign. High Voltage Engineering Corp.

Apparatus for Neutron Detection. A system for detecting the time distribution of neutrons by having them strike a target to generate electrons which are accelerated and passed through a rotating deflecting field to effect a space distribution of deflected electrons and detecting the electrons at points on the circular deflection locus.

U. S. No. 2,767,326. W. M. Stratford. Iss. 10/16/56. App. 5/21/52. Assign. Texaco Development Corp.

Radioactive Exploration. An airborne radioactivity surveying system in which a number of detectors are arranged in a line normal to the direction of traverse and shielded from each other so that each detector receives radioactivity from a different area of the earth's surface, the amplified detector outputs being separately recorded.

U. S. No. 2,768,307. A. L. Tirico. Iss. 10/23/56. App. 7/26/52. Assign. The Texas Co.

Scintillometers. A radioactivity detector having a luminophor whose light falls on a photo-emissive cathode of a light amplifier with a fluorescent target that is optically coupled to the photo-multiplier tube, a high voltage being maintained between the cathode and target of the light amplifier.

U. S. No. 2,768,308. W. W. Schultz. Iss. 10/23/56. App. 11/2/51. Assign. General Electric Co.

Radiation Detector. A radioactivity or X-ray detector having an optically-opaque case containing pieces of a crystal phosphor immersed in a light-transmitting liquid together with a photovoltaic plate which is connected to an external indicating galvanometer.

U. S. No. 2,769,915. C. W. Tittle. Iss. 11/6/56. App. 10/2/52. Assign. Gulf Research & Development Co.

Epithermal Neutron Detector. An epithermal neutron detector having a neutron-gamma reactive

material with a resonance peak for epithermal neutrons and a gamma-ray-responsive scintillating phosphor optically coupled to a photomultiplier tube.

U. S. No. 2,769,916. C. W. Tittle. Iss. 11/6/56. App. 10/2/52. Assign. Gulf Research & Development Co.

Coincidence-Type Slow Neutron Detector. A neutron detector having a neutron-gamma reactive material with a gamma-ray-responsive scintillating phosphor on opposite sides of the material and an optically-opaque material between them, the phosphors being optically coupled to photomultiplier tubes connected to a coincidence circuit.

U. S. No. 2,772,368. S. A. Scherbatskoy. Iss. 11/27/56. App. 8/10/51. Assign. Perforating Guns Atlas Corp.

High Temperature Scintillometer. A photomultiplier tube in which discrimination between high and low energy electrons is obtained by slightly accelerating the electrons from the photoelectric element and having a magnet whose field is transverse to the electron flow to deflect slow electrons.

SEISMIC PROSPECTING

U. S. No. 2,762,032. C. B. Vogel. Iss. 9/4/56. App. 11/26/54. Assign. Shell Development Co.

Seismic Hydrophone. A piezoelectric hydrophone having a pressure-sensitive barium titanate cylinder which is slipped over the cable and closed by end caps and a transformer in the space between the cable and the inside electrode of the cylinder.

U. S. No. 2,763,812. C. D. McKinney, Jr. and M. G. Reitenour. Iss. 9/18/56. App. 9/30/53. Assign. Hercules Powder Co.

Blasting Machine. A condenser-discharge type of shot-firing machine in which a vibrator power supply charges the condenser which discharges through a gas-discharge tube in series with the firing circuit.

U. S. No. 2,763,813. C. D. McKinney, Jr. and M. G. Reitenour. Iss. 9/18/56. App. 9/30/53. Assign. Hercules Powder Co.

Blasting Machine. A condenser-discharge type of shot-firing device having a condenser charged by a vibrator power supply and which discharges through a gas-discharge tube in series with the firing circuit, the tube being triggered by a voltage higher than the firing voltage obtained from a transformer whose primary is also connected to the condenser upon firing.

U. S. No. 2,764,019. N. G. H. Lindholm and S. O. Juselius. Iss. 9/25/56. App. 3/19/53 and 3/3/54.

Vibration Measuring Device. A vibration pickup having an elastically-suspended coil in the annular air gap of a vibrating magnet with the coil connected to a transformer and integrating circuit to indicate the vibration amplitude.

U. S. No. 2,764,658. L. D. Statham. Iss. 9/25/56. App. 10/15/53. Assign. Statham Laboratories, Inc.

Electric Accelerometer. An accelerometer having a cylindrical mass supported at each end by a flexible diaphragm and with axial inertial forces imparted to a wire strain gauge, the space around the mass and on both sides of the diaphragm being filled with oil to produce damping.

U. S. No. 2,765,455. E. P. Meiners, Jr. Iss. 10/2/56. App. 4/18/55. Assign. California Research Corp.

Removing Normal Moveout from Seismic Traces. A device for correcting a seismic record for moveout in which the reproducing heads are mechanically connected to points on a cantilever beam of non-uniform width whose free end is deflected with time along the record and whose width is such as to give the proper variation of moveout with shot-detector distance.

U. S. No. 2,766,400. C. M. Clark and S. W. Martin. Iss. 10/9/56. App. 6/13/55. Assign. California Research Corp.

Methods and Apparatus for Oscilloscopically Displaying a Plurality of Signals. A system for displaying a number of seismic traces on a single-gun c-r tube in which a high-frequency triangular vertical deflection voltage is used and the beam gated only when the deflection corresponds to the trace signal plus a respective voltage to separate the c-r spots.

U. S. No. 2,766,837. B. McCollum. Iss. 10/16/56. App. 11/5/51.

Seismic Exploration Apparatus. An air-shooting device having a cylindrical chamber which is filled with an explosive mixture of gas and air and a detonating chamber which is filled with gas and oxygen, the latter being ignited with a spark plug.

U. S. No. 2,767,388. W. M. Rust, Jr. Iss. 10/16/56. App. 1/22/54. Assign. Esso Research and Engineering Co.

Method of Presenting Seismic Information. A method of presenting seismic data in which the geophone signal controls a pulse generator so that a pulse is recorded at quiescent points of the signal or at the signal peaks.

U. S. No. 2,767,389. B. McCollum. Iss. 10/16/56. App. 11/13/50.

Seismic Exploration Apparatus. A magnetic recorder for compositing records from successive shots by successively recording each shot on a separate channel and automatically playing back, compositing, and rerecording as a single record.

U. S. No. 2,767,973. L. A. G. ter Veen and H. A. Siltamaki. Iss. 10/23/56. App. 1/19/53. Assign. Bendix Aviation Corp.

Accelerometers. A variable air-gap reluctance type vibrometer having a mass supported on two spiders and carrying an armature near an electromagnet.

U. S. No. 2,769,683. J. D. Skelton. Iss. 11/6/56. App. 11/1/51. Assign. Esso Research and Engineering Co.

Variable Density Recording of Galvanometer Motion. An optical system for obtaining a variable-density record with a rotating-mirror galvanometer in which light from a line-filament lamp passes through a filter with graduated transmission in the direction of the filament and after reflection from the mirror a portion of the light passes through a stationary aperture and is focused on the film.

U. S. No. 2,769,929. E. V. Hardway, Jr. Iss. 11/6/56. App. 4/15/53. Assign. Consolidated Electrodynamics Corp.

Electrokinetic Transducers. A displacement transducer having an electrokinetic liquid in two chambers separated by a porous plug and electrodes in the chambers, with a flexible connection arranged to apply a pressure to the liquid in one chamber proportional to the displacement to be detected.

U. S. No. 2,770,193. J. D. Eisler. Iss. 11/13/56. App. 2/1/52. Assgin. Stanolind Oil and Gas Co.

Seismic Wave Generation. A system of air shooting by propelling upward a spreading pattern of charges trailing an electrical detonating connection and detonating the charges simultaneously when in the air.

U. S. No. 2,770,312. D. Silverman. Iss. 11/13/56. App. 9/11/53. Assign. Stanolind Oil and Gas Co.

Seismic Wave Generation. An elongated explosive charge whose average detonation velocity is made the same as the seismic velocity in the surrounding rock by using short lengths of explosive having a higher detonation velocity alternated with short lengths of explosive having a lower detonation velocity.

U. S. No. 2,770,741. M. P. Vore and H. M. Kroft. Iss. 11/13/56. App. 3/4/53. Assign. Westinghouse Electric Corp.

Vibration Pickup. A vibration pickup whose prod is elastically connected to a liquid which fills a closed container having a pressure transducer.

U. S. No. 2,771,592. J. W. E. Edmonson. Iss. 11/20/56. App. 1/9/53.

Detecting and Recording System for Seismic Waves. A variable-area capacitative seismometer having a series of spaced insulating plates with electrodes of different widths so that a uniform rate of capacity change with amplitude is obtained.

U.S. No. 2,771,961. F. G. Blake, Jr. Iss. 11/27/56. App. 7/27/55. Assign. California Research Corp.

Method of Initiating Underwater Seismic Disturbances. A method of reducing the effect of bubble oscillations in underwater shooting by using two simultaneously-detonated vertically-separated charges whose energies and depths are related by the equation: $W_1^2/(D_1+33)^6=W_2^2/(D_2+33)^6$.

U. S. No. 2,772,388. L. W. Erath, P. E. Madeley and P. W. Geery. Iss. 11/27/56. App. 10/18/54. Assign. Southwestern Industrial Electronics Co.

Automatic Volume Control. An avc system for a seismograph amplifier in which the output signal is rectified and applied between the base and emitter of a transistor whose output controls the bias on a pair of diodes which shunt the input signal to ground.

U. S. No. 2,772,405. G. A. Schurman, P. M. Aagaard and F. G. Blake. Iss. 11/27/56. App. 3/24/54. Assign. Calif. Research Corp.

Pressure Detector. A detector array for use in marine seismic exploration having a flexible plastic tube with spaced hollow cylindrical piezoelectric crystals in contact with the inner surface of the tube and with the conductors passing through the opening in the crystals.

WELL LOGGING

U. S. No. 2,761,218. W. J. Bielstein. Iss. 9/4/56. App. 3/23/53. Assign. Esso Research and Engineering Co.

Drill Hole Inclinometer. An inclinometer which may be operated while drilling and having a pendulum with a stepped hole in its end, the pendulum being hydraulically depressed until an index contacts one of the steps, the amount of depression closing holes in a flow plate so that the step contacted may be determined from the mud pressure-flow curve at the surface.

U. S. No. 2,761,977. A. S. McKay. Iss. 9/4/56. App. 3/28/52. Assign. The Texas Co.

Determining the Nature of Earth Formations. A method of correcting a neutron-gamma log for variations in hole diameter by simultaneously measuring the scattered gamma-ray intensity which logs the liquid surrounding the instrument, or a method of correcting a gamma-gamma log by simultaneously running a caliper log and correcting for liquid surrounding the instrument.

U. S. No. 2,763,788. G. Herzog. Iss. 9/18/56. App. 12/22/50. Assign. The Texas Co.

Induced and Scattered Gamma Ray Well Logging. A combined neutron-gamma and gamma-gamma logging sonde having a source of gamma rays and of slow neutrons at its center, a lead shield and detector of energetic gamma rays above the source, and a lead shield and a detector of scattered gamma rays below the source.

U. S. No. 2,764,024. R. C. Rumble. Iss. 9/25/56. App. 1/7/55. Assign. Esso Research and Engineering Co.

Apparatus for Determining Wall Temperature of Casing. A well wall thermometer having a thermistor immersed in liquid heat-transfer medium contained in a metallic block which is pressed against the wall by an insulating body member.

U. S. No. 2,765,412. C. B. Scotty. Iss. 10/2/56. App. 4/20/53. Assign. The Texas Co.

Determination of Porosity and Permeability of Subsurface Formations. A neutron-logging method of determining permeability of uncased hole containing tubing in which a hydrogenous liquid is pumped down the annulus and a non-hydrogenous liquid is pumped down the tubing and up the annulus, a neutron log being run before and after the liquid interface traverses the formation.

U. S. Re. 24,226 (Original No. 2,351,028). R. E. Fearon. Iss. 10/9/56. App. 9/17/41 and 6/13/44. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus. A gamma-ray well logging system using a scintillating crystal whose output is proportional to gamma-ray energy and which is capable of resolving individual pulses.

U. S. No. 2,766,426. E. S. Wilhelm. Iss. 10/9/56. App. 8/3/50. Assign. Socony Mobil Oil Co., Inc.

Total Magnetic Field Well Logging Method and Apparatus. A self-orienting total field borehole magnetometer having three mutually-perpendicular flux valves whose excitation is fed down the cable and the flux-valve signals returned to the surface where one is indicated and the other two are fed to amplifiers and phase-sensitive bridges whose outputs are fed down the cable to the orienting motors.

U. S. No. 2,768,684. J. H. Castel and H. C. Waters. Iss. 10/30/56. App. 2/20/52. Assign. Perforating Guns Atlas Corp.

Well Perforating and Logging Methods and Apparatus. A combined casing-collar locator and gun perforator operating over a single conductor cable having a collar-locating coil connected in a bridge circuit at the surface and excited by a current smaller than that required to fire the gun.

U. S. No. 2,768,701. G. C. Summers. Iss. 10/30/56. App. 2/24/53. Assign. Socony Mobil Oil Co. Inc.

Mud Correction for Velocity Well Logging. An acoustic logging apparatus having a caliper arm, which controls a delay circuit connected between the first transducer and the timing circuit so as to correct for the time delay due to variations in borehole diameter.

U. S. No. 2,769,096. H. B. Frey, Jr. Iss. 10/30/56. App. 4/9/52. Assign. Schlumberger Well Surveying Corp.

Multiple-Target Sources of Radioactive Radiations and Methods Employing the Same. A borehole-accelerator type of radioactive source using two or more ion sources and spaced targets which form spatially-separated sources for making a differential log, or using targets which generate particles of different energy for making different logs.

U. S. No. 2,769,914. C. Goodman. Iss. 11/6/56. App. 11/8/51. Assign. Schlumberger Well Surveying Corp.

Apparatus for Logging the Fluorescence and Phosphorescence of Earth Formations Traversed by a Borehole. A radioactivity logging system in which a source is placed in contact with the borehole wall and the optical fluorescence is detected by a photomultiplier tube coupled to the borehole wall surrounding the source, or phosphorescence is detected by coupling the photo-tube to the borehole wall above or below the source.

U. S. No. 2,769,918. C. W. Tittle. Iss. 11/6/56. App. 10/2/52. Assign. Gulf Research & Development Co.

Epithermal Neutron Logging Method Using Collimation. A neutron-neutron logging method having a neutron source with channels lined with a neutron-absorbing material to collimate the incident neutron beam and a similar lined channel to restrict the solid angle subtended by the neutron detector.

U. S. No. 2,769,920. S. Krasnow. Iss. 11/6/56. App. 7/24/42, 2/27/52, and 4/1/52. Assign. Schlumberger Well Surveying Corp.

Radioactivity Responsive Systems for Use in Boreholes. A radioactivity logging method in which the sonde has two spaced detectors whose signals are combined to obtain a differential log or has two detectors of different dimensions to obtain different types of logs.

U. S. No. 2,770,308. D. F. Saurenman. Iss. 11/13/56. App. 8/11/54. Assign. Schlumberger Well Surveying Corp.

Borehole Apparatus Operated by the Well Fluid. A hydraulic actuator for a borehole apparatus in which solenoid valves operated alternately permit discharge of high-pressure well fluid into a low-pressure container through a cylinder with a piston for actuating the apparatus.

U. S. No. 2,770,736. S. Krasnow. Iss. 11/13/56. App. 4/10/42, 3/12/52 and 4/8/52. Assign. Schlumberger Well Surveying Corp.

Radioactive Method for Marking Borehole Formations. A method of marking a location in a borehole by firing into the borehole wall a bullet containing a substance which can be artificially radioactivated, exposing the borehole wall to activating radiation and detecting the induced activity.

U. S. No. 2,770,771. N. A. Schuster. Iss. 11/13/56. App. 6/6/52. Assign. Schlumberger Well Surveying Corp.

Well Logging Methods and Apparatus. An electric logging system in which potentials at a number of electrodes in an array are measured under conditions of current flow from a center electrode and from end electrodes, and fed into a computer which computes the resistivity of the formation opposite the center electrode.

U. S. No. 2,770,773. E. H. Cooley. Iss. 11/13/56. App. 12/27/54. Assign. Stanolind Oil and Gas Co.

Detecting Corrosion of Well Casing. A magnetic testing device having pole pieces which conform to the inside of the casing and which magnetize the casing to saturation and also having a series of coils on small pole pieces on a neutral plane between the magnetizing pole pieces, the small coils being connected as adjacent arms of a bridge circuit to detect magnetic inequalities in the casing.

U. S. No. 2,770,887. A. R. Barnett, O. Suter and A. J. Abs. Iss. 11/20/56. App. 1/9/51. Assign. Technical Oil Tool Corp., Ltd.

Directional Inclination Recording Apparatus. A well surveying apparatus having a pivotally-supported pendulum carrying a compass magnet, the chart being periodically brought against an index point on the pendulum and rotated a predetermined angle between registrations.

U. S. No. 2,771,685. J. C. Kinley. Iss. 11/27/56. App. 6/12/52.

Internal Pipe Calipering Tools. A calipering device having a number of feelers which mechanically engage inclined surfaces on a motion-transmitting mechanism arranged to record the movement of the feeler that moves farthest outward and the movement of the feeler that moves farthest inward.

U. S. No. 2,771,686. H. C. Hamontre, F. G. Mueller and F. E. Armstrong. Iss. 11/27/56. App. 8/21/53.

Instrument to Measure the Diameter of Subsurface Well Bores. A caliper logging apparatus in which the caliper arms are extended by a motor remotely controlled from the surface and the arms regulate resistance units whose values are indicated at the surface.

U. S. No. 2,771,960. N. J. Smith. Iss. 11/27/56. App. 9/11/51. Assign. California Research Corp.

Interval Velocity Seismic Logging. A seismic logging system using a shaped charge whose cavity faces the borehole wall and having an elastic-wave absorber between the seismometer and the shooting gun so as to eliminate cable-transmitted arrivals.

(See also Patents 2,764,695; 2,765,411; 2,765,418; 2,768,307; 2,769,915; 2,769,916; 2,772,368, listed under RADIOACTIVITY PROSPECTING.)

MISCELLANEOUS

U. S. No. 2,763,857. G. E. Valley, Jr. Iss. 9/18/56. App. 11/15/45. Assign. U. S. A.

Two Station Navigation System. A radio location system in which the mobile station measures the time difference between signals from two spaced transmitters and also obtains from one of the transmitters a signal indicative of the time required for a signal to travel from one transmitter to the mobile transponder thence to the other transmitter, so that both the sum and difference of travel times from the fixed transmitters to the mobile station are measured.

U. S. No. 2,765,117. G. B. Loper. Iss. 10/2/56. App. 5/14/51. Assign. Socony Mobil Oil Co., Inc.

Electronic Beam Controlled Multiplication. A device for multiplying voltages by deflecting an electron stream with one voltage and controlling the potential of a pair of grids with the other voltage and measuring the magnitude of the electron stream which reaches a plate in its path.

U. S. No. 2,768,247. C. I. Beard and R. L. Mills. Iss. 10/23/56. App. 4/22/52. Assign. Socony Mobil Oil Co., Inc.

Stabilized Low Frequency Amplifier with Drift Correction. A low-frequency c-r tube amplifier for removing a drift voltage from a recurring signal and having a periodically-closed feedback circuit which adds the output to the signal at moments of zero voltage in the recurring signal.

U. S. No. 2,768,374. W. M. Rust, Jr. Iss. 10/23/56. App. 6/1/53. Assign. Esso Research and Engineering Co.

Radio Frequency Surveying System. A phase-comparison type of radio surveying system operating on a programmed sequence in which a master station radiates a continuous wave for a short time during which two spaced beacon stations are automatically synchronized in frequency and phase to the received master signal which they subsequently reradiate, the mobile station observing phase differences between the various signals.

U. S. No. 2,768,793. L. F. Bonner. Iss. 10/30/56. App. 3/22/54. Assign. Esso Research and Engineering Co.

Disintegrator for Rock and the Like. A device for crushing rock samples and retaining released hydrocarbons having a chamber and a plunger with hardened blades, the plunger being driven against the rock sample by a manually-actuated hammer sliding on the plunger.

U. S. No. 2,769,335. W. K. Moennig and O. C. Holbrook. Iss. 11/6/56. App. 3/20/53. Assign. The Pure Oil Co.

Mounting Oil Well Cores. A method of mounting a core sample for flow studies by placing it in a container and pouring around the sample a molten alloy of bismuth, lead, tin, and cadmium which expands upon solidification.

SELECTED LIST OF U. S. PATENTS

ISSUED DURING SEPTEMBER, OCTOBER, AND NOVEMBER OF 1956

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,761,160	404	2,763,235	224	Re. 24,226[a]	304
2,761,218[a]	192	2,763,729	224	2,765,565	108
2,761,219	216	2,763,730	484	2,765,649	216
2,761,315	16, 68	2,763,782	316	2,765,652	140
2,761,316	200	2,763,784	140	2,765,654	428
2,761,317	288	2,763,788[a]	304	2,765,656	148
2,761,318	288	2,763,812[a]	32	2,765,981	68
2,761,383	48	2,763,813[a]	32	2,766,094	16
2,761,385	136	2,763,838	68	2,766,328	224
2,761,386	136	2,763,857[a]	312	2,766,400[a]	360, 364
2,761,467	200	2,763,858	316	2,766,401	16
2,761,620	68	2,764,019[a]	492	2,766,406	200
2,761,621	68	2,764,020	492	2,766,421[a]	124
2,761,910	224	2,764,023	460	2,766,422[a]	320
2,761,911	224	2,764,024[a]	452	2,766,424	228
2,761,924	200	2,764,178	200	2,766,425	228
2,761,968	68	2,764,310	520	2,766,426[a]	220
2,761,974	236	2,764,344	68	2,766,427	40
2,761,975[a]	168	2,764,463	224	2,766,429	4
2,761,976	168	2,764,464	324	2,766,449	316
2,761,977[a]	304	2,764,556	140	2,766,617	428
2,761,981	484	2,764,634	224	2,766,619	16
2,761,997	140	2,764,657	68	2,766,621	148
2,762,032[a]	108, 376	2,764,658[a]	4	2,766,627	16
2,762,043	312	2,764,676	68	2,766,837[a]	360
2,762,123	16	2,764,695[a]	308	2,766,931	68
2,762,132	520	2,764,702	484	2,766,932	16
2,762,302	136	2,764,733	140	2,766,933	68
2,762,391–393	288	2,764,755	312	2,766,934	68
2,762,394	288	2,764,909	416	2,766,950	224
2,762,447	12	2,764,937	48	2,766,954	16, 68
2,762,562	68	2,764,938	48	2,767,064	168
2,762,563	68	2,765,115	68	2,767,253	224
2,762,564	68	2,765,117[a]	68	2,767,254	224
2,762,926	236	2,765,406	236	2,767,317	236
2,762,927	236	2,765,408	236	2,767,318	236
2,762,928	236	2,765,409	168	2,767,319	236
2,762,993	16	2,765,310	200	2,767,320[a]	172
Re. 24,222	116	2,765,411[a]	308	2,767,321	196
2,763,153	12	2,765,412[a]	284, 304	2,767,324[a]	308
2,763,154	140	2,765,418[a]	308	2,767,326[a]	308
2,763,157	16	2,765,455[a]	360	2,767,338	484
2,763,211	136	2,765,461	312	2,767,360	148

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	Subject	Patent No.	Subject	Patent No.	Subject
2,767,385	108	2,768,529	412	2,769,929[a]	484, 376
2,767,386	108	2,768,684[a]	48, 220	2,769,930	484
2,767,387	484	2,768,701[a]	8	2,769,935	68
2,767,388[a]	360	2,768,785	68	2,769,950	16
2,767,389[a]	356, 364	2,768,793[a]	88	2,769,956[a]	124
2,767,476	428	2,768,795	224	2,769,976	312
2,767,577	428	2,769,031	12	2,769,977	312
2,767,580	148	2,769,036	224	2,770,044	68
2,767,581	148	2,769,037	224	2,770,130	148
2,767,582	148	2,769,038	484	2,770,131	148
2,767,584	148	2,769,070	484	2,770,133	200
2,767,585	200	2,769,072	252	2,770,134	288
2,767,586	200	2,769,093	236	2,770,145	68
2,767,655	136	2,769,094	308	2,770,162	252
2,767,908	68	2,769,096[a]	304	2,770,193[a]	360, 136
2,767,909	68	2,769,098	308	2,770,308[a]	116
2,767,910	68	2,769,139	252	2,770,312[a]	360
2,767,911	68	2,769,140	252	2,770,415	68
2,767,913	68	2,769,142	324	2,770,429	16
2,767,915	68	2,769,158	108	2,770,452	16
2,767,917	68	2,769,161	484	2,770,703	288
2,767,919	68	2,769,164	308	2,770,735	236
2,767,973[a]	4	2,769,335[a]	88	2,770,736[a]	520, 304
2,768,049	324	2,769,336	88	2,770,741[a]	492
2,768,050	324	2,769,337	148	2,770,771[a]	116
2,768,069	168	2,769,339	188	2,770,773[a]	220
2,768,244	224	2,769,341	288	2,770,774[a]	232
2,768,246	484	2,769,343	16	2,770,795	12
2,768,247[a]	344, 352	2,769,366	416	2,770,797	68
2,768,265	196	2,769,591	68	2,770,887[a]	192
2,768,301	236	2,769,592	68	2,770,890	216
2,768,302	236	2,769,603	16	2,770,966	12, 140
2,768,303	236	2,769,615	80	2,770,969	148
2,768,304	236	2,769,680	68, 324	2,771,034	136
2,768,305	236	2,769,681	324	2,771,243	68
2,768,306	196	2,769,683[a]	360, 364	2,771,244	68
2,768,307[a]	308	2,769,866	224	2,771,512	484
2,768,308[a]	308	2,769,867	484	2,771,513	484
2,768,343	16	2,769,868	40	2,771,514	484
2,768,350	160	2,769,884	196	2,771,515	484
2,768,364	484	2,769,910	236	2,771,581	12, 68
2,768,370	168	2,769,911	236	2,771,592[a]	376
2,768,372	316	2,769,913	308	2,771,595	68
2,768,374[a]	312	2,769,914[a]	152	2,771,596	68
2,768,421	484	2,769,915[a]	308	2,771,685[a]	44
2,768,447	428	2,769,916[a]	308	2,771,686[a]	44
2,768,524	12	2,769,918[a]	304	2,771,770	496
2,768,525	428	2,769,919	196, 324	2,771,771	148
2,768,527	196	2,769,920[a]	304	2,771,772–773	148
2,768,528	148	2,769,921	308	2,771,774	200

Patent No.	Subject*	Patent No.	Subject*	Patent No.	Subject*
2,771,775	460	2,772,059	16	2,772,366	236
2,771,778	16	2,772,135	224	2,772,368[a]	308
2,771,779	16	2,772,336	196	2,772,388[a]	372
2,771,897	68	2,772,361	308	2,772,391[a]	232
2,771,960[a]	8	2,772,362	236	2,772,397	68
2,771,961[a]	360	2,772,364	236	2,772,405[a]	360
2,772,050	68	2,772,365	236	2,772,409	148

REVIEWS

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CONTENTS

Antarctica in the International Geophysical Year, American Geophysical Union, by *W. T. Born*.. 453
Exploration for Nuclear Raw Materials, Robert D. Nininger, by *Travis H. Redman*..... 454
Geophysical Case Histories, Volume II, Paul L. Lyons, by *W. T. Born*..... 454
The New Dallas Seismological Observatory at Southern Methodist University, Louis V. Hull, by *W. T. Born*..... 455
Scientific Uses of Earth Satellites, James A. Van Allen, by *Norman Ricker*..... 455

Antarctica in the International Geophysical Year, American Geophysical Union, Washington, D.C., 1956, 140 pp.+map $6.00.

The activities planned during the International Geophysical year have focused popular attention upon the Antarctic. Those readers of Geophysics who may have more than a passing interest in that largely unexplored continent will welcome this publication of the American Geophysical Union. The volume is a collection of 16 papers originally given at an Antarctic Symposium sponsored by the Union in April, 1956, under the chairmanship of Dr. L. M. Gould. The purpose of the Symposium was to summarize concisely the available scientific information about the Antarctic to form a background for the extensive investigations to be conducted during the International Geophysical Year. The papers included are not limited to geophysical topics but include other related areas of general interest.

Two general papers, one by Joseph Kaplan and one by H. Wexler, outline the program of work being planned and explain why the Antarctic is a "geophysicist's paradise." Among other reasons, it is the cold storage vault for 86 percent of the world's ice. It is the world's most efficient cold air factory. It contains the South Magnetic Pole and is an ideal location for the study of the thermal and electrical properties of an atmosphere cut off from sunlight.

Four papers deal with geographical and meteorological topics, two with geology, four with the physics of the upper atmosphere, and two with the flora and fauna of the Antarctic.

None of the papers deal with previous seismic studies or gravity determinations, indicating that such data are practically non-existent. An article by Ewing and Heizen outlines the seismic refraction studies needed to determine the crustal structure of the shelf area of Antarctica. It is expected that such work will be included in the IGY program. It is also planned to make extensive use of the seismic reflection method for the determination of ice cap thickness and the geological structure in the interior of the continent. Numerous gravity determinations will be made. A number of seismograph stations will be set up to record earthquake phenomena.

Included with the book is a circum-polar map of Antarctica especially prepared for the IGY by the American Geographical Society.

W. T. Born

Exploration for Nuclear Raw Materials, Robert D. Nininger, Assistant Director for Exploration, United States Atomic Energy Commission. D. Van Nostrand Company, Inc., Princeton, New Jersey, $7.50.

This book is one of the Geneva Series on the peaceful uses of atomic energy edited by James G. Beckerley of Schlumberger Well Surveying Corporation. As such an entity, it fills a logical niche in the framework of this series, the purpose of which is to disseminate knowledge incident to the evolution of a technology destined to change the way of life for all of us.

The author has digested from many of the papers presented at the International Conference on the Peaceful Uses of Atomic Energy in Geneva those sections dealing with his assigned phase of the series.

The book is divided into two parts. The first, the Geology of Uranium and Thorium, and the second, Techniques of Prospecting for Uranium and Thorium. Nininger has arranged his material in a logical sequence commencing with the description of the original sources, going through the mechanisms of transport and deposition. Approximately one-third of the volume is dedicated to geological topics.

The second part of the book depicts in considerable detail virtually all of the existing methods and techniques of exploring for an evaluating uranium and thorium deposits. The methods described include geological prospecting, radiometric prospecting, geophysical prospecting, geochemical prospecting, botanical prospecting, hydrogeochemical prospecting as well as the more direct exploration drilling technique.

This compilation has been effectively achieved and should be acceptable to the non-technical layman and exploration engineer alike as a source of general background information in this field.

TRAVIS H. REDMAN
The Texas Company
Texas-Zinc Minerals Corporation
Grand Junction, Colorado

Geophysical Case Histories, Volume II, Paul L. Lyons, Editor, Society of Exploration Geophysicists, Tulsa, Oklahoma, 1956, 641 pp., $7.00 ($6.00 to S.E.G. Members).

By compiling and publishing a series of Geophysical Case Histories, the Society of Exploration Geophysicists has rendered a great and lasting service not only to its own members, but to all individuals and companies engaged in activities which do or could employ geophysical prospecting methods to advantage.

The value and importance of the present volume is well illustrated by the fact that the Oil and Gas Journal saw fit to make it the subject of one of its "Tech Reports" occupying 11 pages in its November 5, 1956, issue. Such an extensive review of any book is extremely rare, if not unique, in publishing circles.

The first volume of the Case Histories, published in 1948, contained some 61 papers. Volume II, now published, contains 53 papers, of which about one-half are papers never before published. The others are reprints from GEOPHYSICS or other journals. The papers were assembled by a committee of the Society of Exploration Geophysicists directed by Mr. D. P. Carlton. The arrangement of papers in the present volume is by type of trap found, rather than by geographical location. However, the index to papers is so arranged that the locale of each case history is easily found. All portions of the world are represented with the exception of the U.S.S.R. and its satellite countries.

Some 23 papers are concerned with anticlinal structures, as against only three dealing with stratigraphic traps and three with reefs. It may be assumed that this distribution represents the relative success of geophysical methods in delineating these three types of structures. However, it is more likely that many discoveries of reef and stratigraphic structures have been made in recent years. There must occur a considerable lag in time between the discovery of an oil field and the publication of its case history, since oil companies necessarily cannot release current information without losing a competitive advantage.

One section of the volume is devoted to new and unusual uses of geophysical methods. One paper

by Daniel Linehan, S.J., describes the application of seismic techniques to the field of archeology, in particular to the investigation of buried structures beneath St. Peters Basilica in Rome.

Three papers dealing with mining problems are included in one short section. Two of these come from Japan, while one describes the discovery of a copper ore deposit in Arizona by a program of magnetic and electro-magnetic surveys supplemented by core drilling.

Of unusual interest, because of the recent discovery date, is a paper by Raoul Vajk and George Walton describing the work leading to the discovery of the Parentis Oil Field, France. In this paper, as well as in a number of others originating in Europe, there is a discussion of the use of telluric currents as a means of locating structure. This method proved to be of no value in the Parentis area. However, in several other papers by European authors, the method is stated to have been of considerable value in delineating gross structure.

Although only three of the papers deal with stratigraphic traps, these deserve careful study. It is a fact of great significance that in two cases, namely the Golden Trend area of Oklahoma, and Majeau Lake, Alberta; discoveries followed a critical re-examination of existing seismic records. How many other traps lie awaiting discovery in records filed and forgotten?

W. T. BORN

The New Dallas Seismological Observatory at Southern Methodist University, Louis V. Hull, *Bulletin of the Seismological Society of America*, Vol. 46, No. 4, 1956, pp. 321–330.

An earthquake occurring in April, 1952, with epicenter in Central Oklahoma, focused attention on the need for a first-class seismological station located in the Southwest to fill in the 1200-mile gap between existing stations at Fayetteville, Arkansas, and at Tucson, Arizona. The Dallas Geophysical Society decided to do something about it, and their effort resulted in the establishment of the Seismological Observatory of Southern Methodist University.

The Dallas Geophysical Society raised the sum of $12,000 by soliciting contributions from individuals and companies in the Dallas Area. These donations were used to purchase equipment. The Southern Methodist University furnished the site, constructed the station and pledged maintenance. A committee of the Society furnished technical assistance.

Many members of SEG will be interested in reading this well-written article by Louis V. Hull. He describes the installation in detail and outlines some of the problems being investigated. The equipment includes one vertical and two horizontal Benioff seismographs, each driving two galvanometers of different periods for photographic recording. An interesting feature of the installation is a separate visual recorder located in the foyer of the Fondren Science Building of the University.

The new station has been operating successfully since December 14, 1953. Investigations in progress (in addition to routine observations) include a study of possible L_g waves having paths crossing the Gulf of Mexico, study of local quarry blasts, and a study of the significance of microseismic storms which are a notable feature of the records being obtained.

W. T. BORN

Scientific Uses of Earth Satellites, edited by James A. Van Allen, The University of Michigan Press, Ann Arbor, Michigan, 1956, 316 pp., $10.00.

This is one of the most interesting and intriguing books which has come to my attention for some time. It consists of 33 separate reports from the Tenth Anniversary Meeting of the Upper Atmosphere Rocket Research Panel held on January 26–27, 1956, at the University of Michigan in Ann Arbor. Each separate report is complete within itself and most of the reports have an appended list of references.

The book gives an excellent account of the physical research being carried out in the field of earth satellites, which should be of great interest to exploration geophysicists interested in the new area of exploration by means of satellites. The coming earth satellite program for the International Geophysical Year makes this book most welcome at this time especially since numerous computations and numerical values are given to the various parameters which enter into the design and study of satellites.

The scope of the book may best be seen by reference to the following table of contents.

1. The orbit of a small earth satellite
   R. J. Davis, F. L. Whipple, and J. B. Zirker
2. Time available for the optical observations of an earth satellite
   J. B. Zirker, F. L. Whipple, and R. J. Davis
3. Satellite tracking by electronic optical instrumentation
   Harrison J. Merrill
4. Possibility of visual tracking of a satellite
   Donald E. Hudson
5. Interpretations of observed perturbations on a minimal earth satellite
   Jackson L. Sedwick, Jr.
6. Systems design considerations for satellite instrumentation
   L. G. deBey
7. Components for instrumentation in satellites
   H. K. Ziegler
8. Experiments for measuring temperature, meteor penetration, and surface erosion of a satellite vehicle
   Herman E. LaGow
9. Insolation of the upper atmosphere and of a satellite
   P. R. Gast
10. Satellite drag and air-density measurements
    L. M. Jones and F. L. Bartman
11. On the determination of air density from a satellite
    Lyman Spitzer, Jr.
12. Pressure and density measurements through partial pressures of atmospheric components at minimum satellite altitudes
    H. S. Sicinski, N. W. Spencer and R. L. Boggess
13. Meteorological measurements from a satellite vehicle
    W. G. Stroud and W. Nordberg
14. The radiative heat transfer of planet earth
    Jean I. F. King
15. Visibility from a satellite at high altitudes
    V. J. Stakutis and Capt. Joseph X. Brennan, USAF
16. A Lyman alpha experiment for the Vanguard satellite
    T. A. Chubb, H. Friedman and J. Kupperian
17. A satellite experiment to determine the distribution of hydrogen in space
    T. A. Chubb, H. Friedman, and J. Kupperian
18. Ultraviolet stellar magnitudes
    Robert J. Davis
19. Quantitative intensity measurements in the extreme ultraviolet
    H. E. Hinteregger
20. Cosmic-ray observations in earth satellites
    James A. Van Allen
21. Study of the arrival of auroral radiations
    James A. Van Allen
22. Proposed measurement of solar stream protons
    Willard H. Bennett
23. Exploring the atmosphere with a satellite-borne magnetometer
    E. H. Vestine
24. Measurements of the earth's magnetic field from a satellite vehicle
    S. F. Singer

25. Satellite geomagnetic measurements
    J. P. Heppner
26. Geomagnetic information potentially available from a satellite
    Ludwig Katz
27. Ionospheric structure as determined by a minimal artificial satellite
    Warren W. Berning
28. Temperature and electron-density measurements in the ionosphere by a Langmuir probe
    Gunnar Hok, H. S. Sicinski, and N. W. Spencer
29. A satellite propagation experiment
    L. M. Hartman and R. P. Haviland
30. Electromagnetic propagation studies with a satellite vehicle
    Fred B. Daniels
31. Study of fine structure and irregularities of the ionosphere with rockets and satellites
    Wolfgang Pfister
32. Meteoric bombardment
    Maurice Dubin
33. Measurements of interplanetary dust
    S. F. Singer

The typography is very neat and the volume is nicely bound.

Because of the wide interest in the IGY earth satellite program, the volume should have a wide sale among workers in all branches of physics.

The editor of the volume, James A. Van Allen, is a pioneer in high altitude research and is chairman of the department of physics of the State University of Iowa.

NORMAN RICKER
The Carter Oil Company
Tulsa, Oklahoma

PUBLICATIONS RECEIVED

American Journal of Science, v. 254, nos. 11 & 12 (Nov. & Dec., 1956); v. 255, n. 1 (Jan., 1957)
Annales de Geophysique, v. 12, n. 3 (1956)
Bulletin of the Earthquake Research Institute, v. 34, part 3 (Sept., 1956)
Bulletin d'Information de l'U.G.G.I., v. 5, n. 15 (Sept., 1956)
Bulletin of the Seismological Society of America, v. 46, n. 4 (Oct., 1956)
Deutsche Hydrographysche Zeitschrift, v. 9, n. 3 (1956)
Economic Geology, v. 51, n. 7 (Nov., 1956)
Erdöl und Kohle, v. 9, nos. 9, 10 & 11 (Sept., Oct., Nov., 1956)
Geofysiske Publikasjoner, v. 15, n. 5 (1956)
Geological Abstracts, v. 4, n. 4 (Dec., 1956)
Geologie Applique, v. 111, n. 5 (1956)
Geologoski Vjesnik, v. 8–9 (1954–55)
Geophysical Abstracts, v. 166 (July–Sept., 1956)
Geophysical Notes, v. 9, n. 1 (1956)
Geophysical Prospecting, v. 4, n. 4 (Dec., 1956)
Journal Academy Science USSR, Series Geophysical, nos. 9, 10 & 11 (1956)
Journal of Petroleum Technology, v. 9, n. 1 (Jan., 1957)
Journal of the University of Moscow, n. 6 (1956)
Mining Engineering, v. 8, nos. 10, 11 & 12 (Oct., Nov., & Dec., 1956); v. 9, n. 1 (Jan., 1957)
Petroleum Economy, nos. 9, 10, 11 & 12 (1956)
Proceedings of the Cambridge Philosophical Society, v. 52, part 4 (Oct., 1956)
Quarterly Journal of the Geological Society of London, v. 112, part 2 (Nov. 9, 1956)
Review of Scientific Instruments, v. 27, nos. 10, 11 & 12 (Oct., Nov. & Dec., 1956)
Revista do Clube de Engenharia (Rio de Janeiro), nos. 243 & 244 (Oct. & Nov., 1956)
Rocznik, v. 25, n. 1 (1956)
Science, v. 124, nos. 3225–3235; v. 125, nos. 3236–3239
Science Reports of the Tohoku University, 5th Series, Geophysics, v. 8, n. 1 (Nov., 1956)
Scientific Monthly, v. 83, nos. 5 & 6 (Nov., & Dec., 1956); v. 84, nos. 1 & 2 (Jan & Feb., 1957)
Soviet Physics JETP, v. 3, nos. 3, 4 & 5 (Oct., Nov. & Dec., 1956)
Tellus, v. 8, n. 3 (Aug., 1956)
Transactions American Geophysical Union, v. 37, n. 5 & 6 (Oct. & Dec., 1956)

MEMORIAL

CHARLES ANDREW ARSENAULT

On September 1, 1956, Charles Andrew Arsenault died in a Houston hospital. With his passing, Sohio Petroleum Company lost an outstanding geophysicist, his friends a true and trusted associate, and his family a devoted husband and father. Funeral services were held September 3, 1956, in St. Mary's Church, Orange, Texas.

Charles was born of French parents on July 24, 1923, in Orange, Texas. Here he spent his boyhood, attending St. Mary's Grade School and Orange High School, graduating in 1940. He was subsequently employed by the Livingston and Houston Shipbuilding Corporation until January 1943. At that time he entered the United States Navy, serving in Scotland, England, France, Belgium and Canada. While in the service he also attended the Naval Training School at Dearborn, Michigan, where he graduated in engineering.

He entered the University of Houston in March 1946. Shortly thereafter he married his sweetheart from Orange, Emily Yvonne Lafitte. In August of 1946 he was employed by Sohio Petroleum Company as a part-time draftsman in the

geology department at Houston. By attending college classes at night and on weekends, he graduated in 1949 with a bachelor of arts degree in geology. This marked the beginning of his geophysical career with Sohio as he advanced through the positions of geophysical computer, seismologist, geophysical party manager, party chief, and geophysicist, to district geophysicist, the position he held in Houston at the time of his death.

While attached to several seismic crews Charles worked in Louisiana, Texas, Kansas and Oklahoma. It was said of him that he was consecrated to his job, and he was often found working records and contouring maps at odd hours of the night. This characteristic held true even after he was stricken, and he insisted upon taking an experimental magnetic seismic crew into the field to reshoot one of his favorite areas. In doing so he set a production record for this type of work.

Charles' strong desire to find oil was rewarded early in his career with Sohio. While acting as seismologist on a reflection seismograph crew he discovered a major structure in St. Landry Parish, Louisiana. This excellent work resulted in the discovery of the Mt. Washington field. He had hoped to publish a case history of this discovery upon completion of drilling but did not live long enough to achieve this goal.

Charles liked to fish and hunt on the rare occasions when his friends could persuade him to leave his work, and he became a keen marksman. In addition to being an active and honored worker in the Catholic Faith he held membership in the Society of Exploration Geophysicists and its Houston Section.

He is survived by his wife and two young sons, George Frederick and Thomas Bradley.

BROOKS STEWART

MEMORIAL

DONALD CRARY

Donald Crary and his wife, Maple, met a tragic death in an airplane accident near Bryan, Texas, the night of January 25, 1957. Don was returning to Oklahoma City after a business trip to Houston, when the plane developed motor trouble and crashed while attempting an emergency landing.

Don was loved and respected by all who worked with him, as well as the many members of the geophysical profession with whom he had associated. He was an outstanding example of a man who availed himself of the opportunities afforded a geophysicist in the profession of oil exploration, since he had progressed from a helper on a seismic crew to division manager of a major company.

Don was born November 30, 1917, at Pierrepont, New York. He completed his elementary schooling at Canton, New York, and attended Lehigh University, receiving a Bachelor of Science degree in mining engineering and geophysics in 1938. During the latter part of 1956, Don attended the advanced management program at Harvard Business School to develop further his natural ability as a leader and manager in the field of petroleum exploration and production. He was

a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, Geological Society of America and American Petroleum Institute.

Immediately following Don's graduation from Lehigh University, he was employed by The Carter Oil Company as a trainee in their geophysical department. In 1939, he joined Independent Exploration Company, and from then until 1946 he progressed from geophysical helper to seismic party chief. Early in 1946, he was employed by Sohio Petroleum Company as a geophysicist in Houston, Texas. Don was an excellent geophysical interpreter with a thorough understanding of the gravity and seismic methods, and with an outstanding ability to coordinate geophysical and geological subsurface information. These qualities made it possible for him to advance rapidly in the Sohio organization, and by 1949 he was named superintendent of exploration for the company. Early in 1953, Don was named manager of Sohio's Northwest Division where he very ably organized and managed the company's activities in the Rocky Mountains and Canada for a period of three years. Late in 1956, he was transferred to Oklahoma City as manager of the exploration staff, reporting to the general manager.

The geophysical profession has lost in Don Crary one of its staunchest champions and one of the most effective voices in oil company management; a man who progressed through geophysics to a managerial position, entirely upon his own merits and personality. He was at all times ready to help and to teach younger people and was sincerely respected by all his business associates.

Don met his wife, Maple Lee Magouyrk, at Lufkin, Texas, in 1941, and they were married in 1942. They were a devoted couple, dedicated to their family, and were energetic and conscientious leaders in the Methodist Church in the several cities in which they lived. They are survived by their four children, Martha Elaine, Sarah Ella, Don, Jr., and John Albert. Their passing has left a tragic mark on those with whom they were associated. The geophysical profession has indeed lost a truly outstanding leader from its ranks. Don will long be remembered by all of those whose privilege it was to know him.

ROY F. BENNETT

OKLAHOMA CITY, OKLAHOMA
February 15, 1957

MEMORIAL

EVERETTE LEE DEGOLYER

Everett Lee DeGolyer passed away on December 14, 1956, after several years' illness.

His passing was mourned by his wife, Mrs. Nell Virginia (Goodrich) DeGolyer, four children, Nell Virginia, Dorothy Margaret, Cecilia Jeanne, and Everette Lee, Jr., and by thirteen grandchildren. His passing was also mourned by hundreds of friends whom he had made, not only throughout the United States, but throughout the world. He was affectionately known as Dee.

Dr. DeGolyer was born near Greensburg, Kansas, October 9, 1886. Subsequently, his family moved to Oklahoma where he graduated from the University of Oklahoma in 1911 as a geology major with an A.B. degree.

He entered the field of his chosen profession as a geologist on the staff of the U. S. Geological Survey, and held this position from 1906 until 1909. In 1909 he entered the services of Mexican Eagle Oil Company in Mexico as a geologist and rapidly rose to the position of chief geologist during the ensuing five years. His services to the Mexican Eagle Oil Company during this five-year period were

outstanding, as he is credited with having made the location for the tremendous discovery well on the famous Golden Lane of Mexico. In 1919 he moved to New York City and participated in the organization of Amerada Corporation and Rycade Oil Corporation with the financial support of the Pearson interests of England.

During the next thirteen years he was the driving spirit of Amerada Corporation, and rose rapidly from vice president to president and then to chairman of the board. He resigned this latter position in 1932. During this period he was also vice president and then president of Rycade Oil Corporation.

Dr. DeGolyer, with the characteristic foresight and vision for which he ultimately became so famous, introduced the gravity meter into the United States in 1923, and shortly thereafter (in 1925) organized the Geophysical Research Corporation. The Geophysical Research Corporation equipped the refraction seismograph with electro magnetic detectors and, as a part of the seismic survey system, provided a radio method of recording the time of firing the shot. This permitted the measurement of the distance from shot point to recorder by means of the air-sound wave; thereby eliminating the need for surface surveying. In 1926 the Geophysical Research Corporation, based on the early work of Haseman, McCullum, Eckhart, and Karcher undertook the development of a practical reflection seismograph. In 1928 field exploration surveys were being conducted for the Amerada Corporation with the reflection seismograph; and in 1929 the Amerada Corporation made the first oil-field discovery resulting from the use of the reflection seismograph. This field is known as the Edwards Pool, located near Seminole, Oklahoma. DeGolyer maintained an active interest in the development of geophysical prospecting methods until 1941.

In 1936 he organized the oil-field appraisal firm of DeGolyer and MacNaughton and was the senior member of the firm until his death. During the past twenty-four years he resided in Dallas, Texas.

He was a past president of the American Institute of Mining and Metallurgical Engineers and of the American Association of Petroleum Geologists. Throughout his professional life he held many offices and served on many committees connected with government and civil activities related to the oil industry.

Because of DeGolyer's early recognition of the possibility of these various geophysical devices, and his prompt and successful use of them in the discovery of new oil fields, he was awarded the Lucas medal by the American Institute of Mining and Metallurgical Engineers, the John Fritz medal of the Associated Engineering Societies, and the Sidney Powers gold medal by the American Association of Petroleum Geologists. He was also awarded the honorary degree of Doctor of Science by Colorado School of Mines, Southern Methodist University and Tulane University. He was awarded the degree of LL.D. by Trinity College, Princeton University, University of Mexico, and Washington University. He was an honorary member of Phi Beta Kappa, Tau Beta Pi, Sigma Xi, and the recipient of many other honors too numerous to mention here.

He was one of the first honorary life members to be elected to the Society of Exploration Geophysicists and was so elected in 1930.

In addition to his many successes in the field of oil exploration, DeGolyer was an avid reader and prominent collector of early Americana, with particular emphasis on Spanish exploration in the Southwest and on early Texas history. He collected and gave a great deal of this material to the libraries of the University of Oklahoma and the University of Texas. He made a number of other lesser contributions to other colleges and universities in the country, including Princeton University and Southern Methodist University.

His great interest in literature was shown by his sponsorship of the magazine *Saturday Review of Literature*, of which he was chairman of the board.

DeGolyer had an affable and inviting personality, probably much of which he inherited from his gracious mother. Because of his wide range of interests, he was an exceptionally interesting conversationalist and his association was sought by hundreds of people in all walks of life.

One of the great men in the history of oil-field exploration has passed away and has left his footprints upon the sands of time. These footprints will be in evidence as long as oil is being produced.

J. C. KARCHER

DALLAS, TEXAS
January 7, 1957

MEMORIAL

ROBERT TREAT PAINE THOMPSON

It is with extreme regret that we observe the passing of one of our members, Robert Treat Paine Thompson, who died in Austin, Texas, on March 22, 1956, at the age of 63 years.

Bob Thompson was one of the original group of party chiefs who helped launch Geophysical Service Inc. in 1930, a connection he maintained until 1952, when it became necessary to resign because of ill health. He retired at that time to his ranch at Bandera, Texas.

Bob will be long remembered in the petroleum exploration industry as a stalwart person who maintained an integrity of purpose with relentless effort—one of those rare people who are both hard taskmasters and yet kindly individuals. Being naturally convinced that a field party is no better than its leader, he felt his responsibilities keenly. He had the continual deep-seated urge to work hard and to expect his men to perform likewise. His was a high strung existence which carried him through seismic operations in Mexico, India, and Sumatra as well as in south central United States. It is important to note that Bob headed up GSI's

first foreign activity by taking a party to Mexico in 1931. Incidentally, this program—a seismic survey over the present Poza Rica Field—probably was the first reflection work in Mexico.

He was openly proud of the number of young men who started their geophysical careers under his guidance and who have subsequently thrived as a result of the sound training he gave them, not only in the principles of applied seismology, but in the art of sound human relations. He was a patient teacher, except to those who made little effort to learn. Always forthright, he made his position firm and clear so there was never any question as to where one stood with him. It was true that Bob's friendship had to be earned; but once attained, the recipient felt it to be most sincere and heart-warming.

Bob was born in Brenham, Texas, on December 28, 1892. Upon graduating from the University of Texas in 1915 in electrical engineering, he entered the Westinghouse electrical test course at Pittsburgh, Pennsylvania, as a young engineer. With the entry of the United States in World War I he volunteered for the U. S. Corps of Engineers, became a first lieutenant, and saw service in France. Soon after being discharged from the Army he joined the Gulf Oil Company to serve a three-year assignment at Tampico, Mexico. In 1923 he returned to his home town of Brenham, Texas. After a year with the Brenham Compress & Oil Company, he joined the Texas Power & Light Company, where he became manager before being transferred to Dallas. In 1930 he felt the urge to enter the exciting new field of geophysical exploration for petroleum, so Bob was hired by J. C. Karcher and Eugene McDermott as one of the original group of GSI party chiefs. Bob's excellent judgment of people was a wonderful attribute. On June 6, 1935 he had the good fortune to marry Mary Legrande Shacklett.

Bob had been in failing health for several months prior to his fatal heart attack. He was buried at Prairie Lea Cemetery at Brenham, Texas.

Other than his wife, Mary, he had few surviving kinsmen; hence, his tremendous interest in the welfare of his many friends and former associates, all of whom he inspired to seek life's greatest pleasure—the satisfactions which comes from doing one's best and through helping others.

CECIL H. GREEN

December 12, 1956

CONTRIBUTORS

MORGAN J. DAVIS

MORGAN J. DAVIS, formerly vice-president and director in charge of the Exploration Department of Humble Oil & Refining Company, was elected executive vice-president of the Company in May, 1956. He was born in 1898 in Anson, Texas.

He attended Texas Christian University for two years and was graduated from the University of Texas in 1925 with a bachelor of arts degree in geology. During an interim period before graduation he served as a construction engineer for three years on the Tulsa Spavinaw Water Project in the early twenties. He joined Humble as a geologist in the old Cisco Division in June, 1925.

A few months later Mr. Davis went to Roswell, N. M., as geologist in charge of the office there. After four years in New Mexico he joined Nederlandsche Koloniale Petroleum Mij. and was stationed in Java and Sumatra, where he led geological expeditions into several islands of the archipelago and later served as resident geologist in Sumatra.

Mr. Davis returned to Humble in 1934 as district geologist for New Mexico, with headquarters again in Roswell. He remained there until 1936, when he became division geologist for the Gulf Coast Division. He served as acting chief geologist from August, 1940, to February, 1941, at which time he became chief geologist for the company. In 1946 the geologic, lease, and scouting department became the exploration department, and Mr. Davis was made manager of the department in addition to his duties as chief geologist.

In May, 1948, he was elected to the board of directors, and in May, 1951, he was named a vice-president.

Mr. Davis is a past president of The American Association of Petroleum Geologists.

H. F. DUNLAP

H. F. DUNLAP attended Rice Institute at Houston, Texas, receiving his bachelor's degree in physics in 1938, a master's degree in 1939, and a Ph.D. in 1941, all from Rice. During the war he worked on proximity fuse development at Carnegie Institution, Department of Terrestrial Magnetism; and at the University of New Mexico on proximity fuses, hypervelocity projectiles, and supersonic aerodynamics. He joined the Atlantic Refining Company's research and development department in 1945 and has been there ever since. He is presently head of the section engaged in exploration research. He is a member of the Society of Exploration Geophysicists, American Institute of Mining and Metallurgical Engineers, Inc., American Physical Society, and Sigma Xi.

LYNN G. HOWELL received the degrees of Bachelor of Arts and Master of Arts from the University of Texas in 1925 and 1926. He received his Doctor of Philosophy degree in physics from the California Institute of Technology in 1930.

Since 1930 he has been engaged in geophysical research with the Humble Oil & Refining Company.

From 1941 to 1945, he was on leave from the Humble Company with the Section T group at the Department of Terrestrial Magnetism and the Applied Physics Laboratory of Johns Hopkins University in and near Washington, D. C.

He is a member of the American Physical Society, the American Geophysical Union, the Society of Exploration Geophysicists, the Seismological Society of America, Sigma Xi and the Houston Geological Society.

LYNN G. HOWELL

FRANK PRESS

FRANK PRESS received his B.S. degree in physics from the City College of New York in 1944, and his M.S. from Columbia University in 1946. He was teaching assistant in physics, 1945 to 1946, and university fellow, 1946 to 1947 at Columbia. He earned the Ph.D. at Columbia in 1949. From 1952 until 1955 he was associate professor of geophysics at Columbia. In 1955 he became professor of geophysics at California Institute of Technology, a post he now holds.

Dr. Press has been a member of the Society of Exploration Geophysicists since 1950, and a frequent contributor to GEOPHYSICS.

S. BALAKRISHNA

S. BALAKRISHNA was born in August, 1931. He graduated from Andhra University in 1952 with a B.Sc degree and honours. In 1953 he received the M.Sc. degree in geology from the same university. He was awarded the National Institute of Sciences research fellowship in 1954, and since June, 1953, he has been a full time research scholar in the Physical Laboratories, Osmania University, Hyderabad, India. In 1954 he was appointed lecturer in geology of that university. He received the Ph.D. degree in geology at Osmania University in 1955, and at present he is a post-doctoral research fellow in Dunbar Laboratory, Harvard University.

VLADIMIR BARANOV was born in Moscow in 1897, and went to France in the early twenties. He received his degree of engineer from the Ecole des Arts et Manufactures, Paris, in 1927. He then worked for his Ph.D. in mathematics, at the University of Montpelier, receiving the degree in 1941. He has been engaged in geophysical work with the Compagnie Generale de Geophysique, Paris, since 1927, working successively as a party chief, supervisor, and chief of the scientific research division of the company. He is a member of the European Association of Exploration Geophysicists, the Society of Exploration Geophysicists, the Association Francaise des Techniciens du Petrole, the French National Committee of the U.G.G.I., and the French Mathematical Society.

VLADIMIR BARANOV

JOSEPH W. BERG, JR.

JOSEPH W. BERG, JR., a native of Pennsylvania, received his B.S. in mathematics and physics at the University of Georgia and his M.S. and Ph.D. in geophysics at Pennsylvania State University.

He taught mathematics and physics at Armstrong College from 1948 to 1949. He was in charge of geophysics during 1954 and 1955 at The University of Tulsa, and is presently assistant professor of geophysics at the University of Utah.

His professional affiliations are Sigma Pi Sigma, Sigma Xi, American Geophysical Union, Society of Exploration Geophysicists, and Seismological Society of America.

MILTON B. DOBRIN

MILTON B. DOBRIN received the B.S. degree from the Massachusetts Institute of Technology in 1936, the M.S. from the University of Pittsburgh in 1941, and the Ph.D. from Columbia University in 1950. In 1937 he went to work for the Gulf Research and Development Company in the seismic interpretation section. From 1942 to 1947 he was engaged in underwater sound research for the Naval Ordnance Laboratory. From 1947 to 1949 he completed his graduate studies in geology and geophysics at Columbia University, serving from 1948 to 1949 as lecturer in geology.

From 1949 to 1955 he was a senior research technologist at the Field Research Laboratories of the Magnolia Petroleum Company, specializing in research on seismic prospecting. In January, 1956, he joined the geophysical staff of Triad Oil Co., Ltd., Calgary, Alberta.

He was first vice-president of the Dallas Geophysical Society in 1952 and president in 1953. He was editor of GEOPHYSICS from 1953 to 1955 and is now an associate editor.

He is a fellow of Geological Society of America and a member of the American Association of Petroleum Geologists, the American Geophysical Union, the Seismological Society of America, the European Association of Exploration Geophysicists, Canadian Society of Exploration Geophysicists, and the Alberta Society of Petroleum Geologists.

SIDNEY KAUFMAN

SIDNEY KAUFMAN received the A.B. degree in 1930 and the Ph.D. degree in physics and mathematics in 1934, both from Cornell University. From 1934 to 1936 he was a research fellow of the Charles A. Coffin Foundation of the General Electric Company, and in 1936 he was employed by the exploration division of the Shell Oil Company. During World War II, on military leave of absence from Shell, he was attached to the electronics division of the First Naval District as officer-in-charge of NTS (Electronics) and NTS (Loran); during 1945–46 he was principal physicist in the airborne radio division at the Naval Research Laboratories. In 1946 he returned to Shell Development Company as senior physicist in the exploration and production research division. Dr. Kaufman is a member of several scientific societies and is serving on several committees concerned with geophysics and with electronic instrumentation.

M. KRISHNAMURTHI received the B.Sc. degree with honors in 1943, Diploma in Electronics in 1948, and Ph.D. in 1955. From 1948 to 1950 he was development engineer, E.M.I. Engineering Development Ltd., Hayes, England. Since June, 1950, he has been lecturer and senior assistant to the director, physical laboratories, Osmania University, Hyderabad, India. At present he is on leave as post doctorate fellow at the radio observatory, Ohio State University, Columbus, Ohio.

Dr. Krishnamurthi is a member of the British Institute of Radio Engineers.

M. KRISHNAMURTHI

ANTHONY S. LAUGHTON

ANTHONY S. LAUGHTON received his B.A. degree in physics at Cambridge University in 1950. He then carried out post-graduate research in the department of geodesy and geophysics at Cambridge, studying the physical behaviour of ocean sediments under compaction. He also participated in seismic exploration of the deep sea.

In 1954 and 1955, he studied at the Lamont Geological Observatory, Columbia University, N. Y., as the John Murray Research Student of the Royal Society, London. Four months of this period were occupied in geophysical deep-sea expeditions in R/V Vema.

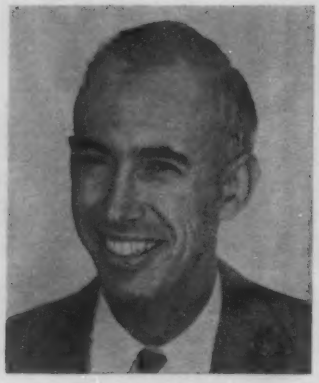
In 1955, he joined the National Institute of Oceanography, Surrey, England, where he is now working on general geological problems of the deep-sea bed, using, in particular, photographic techniques.

He received a Ph.D. (Cantab) in 1956.

PETER MANDEL, JR.

PETER MANDEL, JR. is a native of Pennsylvania. He received his B.S. degree in geophysics and geochemistry from The Pennsylvania State University in 1953. During a subsequent tour of duty with the U. S. Army he attended the officer's radar repair course at the signal school, Fort Monmouth, New Jersey, and later served with an electronic warfare commission unit in the Far East. He received the M.S. degree in geophysics from the University of Utah in 1956. He is currently employed by Standard Oil Company of California, Salt Lake City, Utah, as a geophysicist.

Mr. Mandel is an associate member of the Society of the Sigma Xi and a student member of the Society of Exploration Geophysicists (candidate for associate membership).



JOSEPH D. MARTINEZ

JOSEPH D. MARTINEZ received the B.S. degree in electrical engineering from Louisiana State University in 1937. From 1937 to 1941 he was engaged primarily in sales engineering work. In 1941 he was called to active duty as a reserve officer and served until 1945 as a captain in the infantry. After the war he was employed as an electrical engineer for two years by the Brown Company of Berlin, New Hampshire. During 1948 and 1949 he maintained an office as a consulting electrical engineer in Baton Rouge, Louisiana.

Mr. Martinez returned to Louisiana State University in 1949 for graduate study and received the M.S. degree in geology in 1952. At this time he joined the geophysics research section of the Humble Oil & Refining Company as a senior research geophysicist.

Mr. Martinez is a member of the Geological Society of America, the American Association of Petroleum Geologists, the American Geophysical Union, Sigma Xi, and the Houston Geological Society.

L. L. NETTLETON was born in Nampa, Idaho, and lived there until he graduated from the University of Idaho in 1918. After a year's interlude during the first World War, he went to the University of Wisconsin as a student assistant and graduate student in the physics department, earning a Ph.D. in 1923. He was then in the research department of the Union Switch and Signal Company (makers of railway signal equipment), for five years. He then joined the newly organized research department of the Gulf Oil Company and was in charge of gravity interpretation, through the broad expansion of torsion balance, pendulum and gravimeter methods. In 1946 he moved to Houston as a partner in Gravity Meter Exploration Company, his present position.

L. L. NETTLETON

He is probably best known to geophysicists through his book, *Geophysical Prospecting for Oil*, published in 1940 and based on a course of lectures given for some ten years at the University of Pittsburgh. He has also published some ten papers in GEOPHYSICS, as well as papers in other journals. He holds memberships in the AAAS; Am. Assn. of Pet. Geol.; Geol. Soc. of Am.; Am. Physical Soc.; Am. Geophys. Union; Texas Acad. of Science, Houston Section; SEG and Houston Geol. Soc. He served on the Projects Committee of the G.S.A. (for research grants under the Penrose endowment) and was a member of the Research and Development Board of the Department of Defense.

He has been a member of the SEG since 1936, has served the Society as editor, vice president and president, was editor of *Early Geographical Papers* and *Geophysical Case Histories, Volume I*, has served on various committees and the current list of committee members shows his name in five places. He was elected an honorary member of the society at its 27th annual meeting, in New Orleans.

E. M. PALMER

E. M. PALMER received his A.B. degree in 1930 from Dartmouth College, where he majored in physics. He was an assistant in the research department of the Leeds & Northrup Company until late in 1931 when he was employed by the Gulf Research & Development Company. Until 1941 he was engaged in seismic field exploration and instrumentation. During the war period he was associated with NDRC instrumentation projects and special weapons development at Gulf. Since 1946 he has been working on general geophysical developments and, more recently, closely associated with improvements in the techniques of utilization of seismic data. He is a member of the Society of Exploration Geophysicists, the American Association for the Advancement of Science, and the American Physical Society.

A. L. PARRACK

A. L. PARRACK received a B.S. degree in 1935 and an M.S. degree in 1945 both in Electrical Engineering. In 1951 he obtained a Ph.D. degree in chemistry from Texas A. and M. College. He has been active in research work serving both the Texas Engineering Experiment Station and the Texas A. and M. Research Foundation in the years from 1945 to 1953. In 1953 he joined The Texas Company where he has been devoting full time to seismic research.

Dr. Parrack is a member of the Society of Exploration Geophysicists, The American Chemical Society, Tau Beta Pi, and Sigma Xi.

J. D. SKELTON

J. D. SKELTON received his B.S. degree in Electrical Engineering from Kansas State College and an M.S. degree from Oklahoma A. and M. Since graduation in 1948 he has been associated with The Carter Oil Company in the geophysical research section of their Research Laboratory. Mr. Skelton has been engaged primarily in seismic equipment research with his more recent work being in the design and development of magnetic tape recording equipment for geophysical operations. He is the present chairman of the Society of Exploration Geophysicists magnetic recording committee.

Mr. Skelton is a member of the Society of Exploration Geophysicists, Eta Kappa Nu, Sigma Tau, and Phi Kappa Phi.

ISIDORE ZIETZ

ISIDORE ZIETZ was graduated with a B.S. degree in mathematics in 1939 and a masters degree in 1940 from the College of the City of New York. He is now fulfilling requirements for the Ph.D. in theoretical physics at the Catholic University of America. He was employed by the U. S. Geological Survey as a field topographic engineer in 1941 and has been working with the Survey since that time. He transferred to the Washington, D. C. office in 1942 as a geodetic engineer and served in the U. S. Army from 1944 to 1946 with the 30th Engineers Base Topographic Battalion doing geodetic and topographic work. Upon discharge from the Army, he returned to the U. S. Geological Survey as a geodetic engineer. In 1946 he transferred to the geophysics branch where he has been working for the most part on research in the interpretation of aeromagnetic data. He was a part-time instructor in mathematics at Catholic University from 1946 to 1950 and at Virginia University from June, 1955 to the present.

Mr. Zietz is a member of Sigma Xi and the Society of Exploration Geophysicists.

Biographies and photographs of the following authors appear in earlier issues of GEOPHYSICS as follows: Kenneth L. Cook, v. 21, p. 212; Fraser Grant, v. 17, p. 413; and C. W. Horton, v. 20, p. 710.

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN NOVEMBER, 1957

Executive Committee

President: Roy F. Bennett, Sohio Petroleum Co., Oklahoma City, Oklahoma
Vice-President: J. P. Woods, The Atlantic Refining Co., Dallas, Texas
Secretary-Treasurer: John C. Hollister, Colorado School of Mines, Golden, Colorado
Editor: Norman Ricker, The Carter Oil Co., Tulsa, Oklahoma
Past President: R. C. Dunlap, Jr., Geophysical Service Inc., Dallas, Texas

Nominations

Roy F. Bennett, *Chairman*
R. C. Dunlap, Jr.
Paul L. Lyons

Tellers

W. M. Erdahl, *Chairman*

Education

J. L. Soske, *Chairman*

Student Membership

Richard Brewer, *Chairman*
W. H. Courtier
O. T. Lawhorn
A. W. Musgrave
J. P. Woods

Distinguished Lectures

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W. B. Agocs ('57)
John Bemrose ('59)
Milton Born ('59)
M. E. Denson, Jr. ('58)
R. A. Peterson ('58)

Radio Facilities

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W. M. Rust, Jr., *Vice-Chairman*
C. B. Bazzoni
Richard Brewer
V. Robert Kerr
E. M. Shook
Daniel Silverman
Bart W. Sorge

Membership

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H. E. Itten
E. L. Mount
Bart W. Sorge

Honors and Awards

George E. Wagoner ('57), *Chairman*
Sigmund Hammer ('58)
Curtis H. Johnson ('59)
Roy L. Lay ('60)
Paul L. Lyons ('61)

Publications

Cecil H. Green, *Chairman*
D. H. Clewell
Sigmund Hammer
L. L. Nettleton
H. B. Peacock

Reviews

W. T. Born, *Chairman*
Kumiji Iida
F. K. Levin
Daniel Linehan, S.J.
E. V. McCollum
L. M. Mott-Smith
R. G. Piety
Frank Press
Luigi Solaini

Publicity

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G. A. Burton
John Byers
G. M. Conklin
John G. Cooke, Jr.
H. V. Crowder
H. F. Dodson
Lynn D. Ervin
Russell L. Long
John C. McCaslin
H. G. McCleary
W. A. Meszaros
L. K. Morris
W. R. O'Brien
Lorne H. Reed
K. Watson
Thomas S. West

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F. A. Hale
J. E. McGee
F. O. Mortlock
Ralph B. Ross
Ben F. Rummerfield

Geophysical Activity

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R. J. Copeland
W. W. Hardy
Herbert Hoover, Jr.
Santos Figueroa Huerta
C. N. Hurry
Kumiji Iida
C. C. Lister

Safety

E. L. Johnson, *Chairman*

Case Histories

D. P. Carlton, *Chairman*

Mining Case Histories

Harold O. Seigel, *Chairman*
J. Ewart Blanchard
Kenneth L. Cook
Sherwin F. Kelly
Howard McMurry
Robert G. Van Nostrand

Constitution and Bylaws

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Henry C. Cortes
Andrew Gilmour
Cecil H. Green
Sigmund Hammer
J. J. Jakosky
L. L. Nettleton

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M. D. Butler
John Daly
Milton B. Dobrin
J. G. Ferguson
Paul Greenlea
Otis Hocker
Otto Holekamp
F. G. Knight
J. A. Kurfess
P. E. Narvarte
John F. Partridge, Jr.
Robert E. Rettger
L. O. Seaman
John Sloat
Edward B. Wasson
Stanley Wilcox

Research

H. F. Dunlap, *Chairman*
W. T. Born

J. M. CRAWFORD
C. H. DIX
C. H. GREEN
L. L. NETTLETON
T. J. O'DONNELL
R. A. PETERSON
DANIEL SILVERMAN
J. E. WHITE
J. E. HAWKINS

Research Sub-Committee on University Symposia

R. A. PETERSON, *Chairman*
C. H. DIX
N. A. RILEY

Research Sub-Committee on Thesis Subjects

L. L. NETTLETON, *Chairman*
C. H. GREEN
B. D. LEE

Research Advisory Committee on Rice Institute Symposium

NOYES D. SMITH, JR., *Chairman*
C. H. DIX
R. A. PETERSON
N. A. RILEY
L. L. NETTLETON
B. D. LEE

Index of Wells

V. U. GAITHER, *Chairman*

Magnetic Recording

J. D. SKELTON, *Chairman*
KEITH R. BEEMAN
ROLAND F. BEERS
K. E. BURG
J. D. EISLER
GLENN M. GROSJEAN
J. E. HAWKINS
K. M. LAWRENCE
A. J. W. NOVAK
R. A. PETERSON
R. R. THOMPSON
F. A. VAN MELLE

Magnetic Recording Sub-committee on Definitions & Measurement

L. W. ERATH, *Chairman*
R. A. ARNETT
FRANK COKER
J. M. CUNNINGHAM
J. J. DURAPAU
F. J. FEAGIN
H. R. FRANE
ROGER HARLAN
R. W. KELLEY
L. B. MCMANIS
R. C. MOODY

Magnetic Recording Sub-committee on Recorder Characteristics

S. KAUFMAN, *Chairman*
A. L. PARRACK

Radioactive Mineral Exploration

BEN F. RUMMERFIELD, *Chairman*
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JOHN C. HOLLISTER
RALPH HOLMER
F. H. LAHEE
PAUL L. LYONS
L. W. MACNAUGHTON
JOHN MASTERS
A. GARCIA ROJAS
STAN L. ROSE

American Geological Institute Directors

PAUL L. LYONS ('57)
R. C. DUNLAP, JR. ('58)

Business Office

H. M. THRALLS, *Chairman*
CRAIG FERRIS
JAMES F. JOHNSON

Sustaining Membership

OTIS HOCKER, *Chairman*

International Geophysical Year

PAUL L. LYONS, *Chairman*

National Research Council Div'n of Earth Sciences Representative

(To be appointed)

AAAS Council Representative

ROLAND F. BEERS

LOCAL SECTIONS

Geophysical Society of Tulsa

Chartered February 2, 1948

Pres.: W. M. Erdahl
1st V-Pres.: John J. Rupnik
2nd V-Pres.: James F. Johnson
Treas.: John E. Bondurant
Editor: V. L. Jones
Secty.: Ralph D. Lynn
The Carter Oil Company
Box 801
Tulsa 2, Oklahoma
Meetings: Monthly, 2nd Thursday
7:00 P.M., meeting only
University of Tulsa, room 224,
Petroleum Science Hall

SEG Houston Section

Chartered February 14, 1948

Pres.: W. B. Lee, Jr.
1st V-Pres.: Otis B. Hocker
2nd V-Pres.: Curtis P. Harkins
Treas.: J. D. Watzlavik
Secty.: Ben R. Howard
Warren Petroleum Corp.
801 1st City Nat'l Bank Bldg.
Houston 2, Texas
Meetings: Monthly
Noon luncheon ($1.65)
Rice Hotel

Pacific Coast Section SEG

Charted April 12, 1948
Pres.: Flint H. Agee
V-Pres, N.D.: C. A. Bengston
V-Pres. S.D.: Lawrence S. Morrison
Secty.: John A. Hugus
Western Gulf Oil Co.
900 Wilshire Blvd.
Los Angeles 17, Calif.
Meetings: Monthly, 2nd Thursday
Noon luncheon ($2.00)
Biltmore Hotel, Los Angeles

Dallas Geophysical Society

Chartered August 7, 1948
Pres.: R. E. Rettger
1st V-Pres.: Chester Donnally
2nd V-Pres.: A. W. Musgrave
Secty.: Wm. C. Wooley
Magnolia Petroleum Co.
Box 900
Dallas, Texas
Meetings: Monthly, usually 2nd Monday
8:00 P.M.
Fondren Science Building
Southern Methodist University

Fort Worth Geophysical Society

Chartered August 7, 1948
Pres.: A. E. McKay
V-Pres.: R. C. Herron
Secty.: V. S. Balderson
The Pure Oil Co.
Box 2107
Forth Worth, Texas
Meetings: Monthly, 4th Monday
Noon luncheon ($1.50)
Texas Hotel

Ark-La-Tex Geophysical Society

Chartered March 12, 1949
Pres.: Herbert J. Ferber
V-Pres.: Charles P. Bragg
Secty.: H. L. Grant
Western Geophysical Company
980 Jordan Street
Shreveport, Louisiana
Meetings: Monthly, last Monday
Noon luncheon ($1.50)
Captain Shreve Hotel
Shreveport

Permian Basin Geophysical Society

Chartered January 30, 1950
Pres.: R. M. Pinson
1st V-Pres.: B. F. Owines
2nd V-Pres.: E. E. Fickinger
Treas.: B. A. Heidt
Secty.: J. E. Clark
Box 1018
Midland, Texas
Meetings: Monthly, 2nd Tuesday
7:30 P.M., free coffee & donuts
Midland Womens Club
Midland, Texas

Denver Geophysical Society

Chartered May 19, 1950
Pres.: E. B. Wasson
V-Pres.: C. E. Riddell
Secty.: R. R. Parks
The Chicago Corporation
333 Logan Street
Denver, Colorado
Meetings: Monthly, 1st Monday
5:30 P.M., meeting only
Petroleum Club, Denver

Canadian SEG

Chartered January 24, 1952
Pres.: George J. Blundun
V-Pres.: John Fuller
Secty.: Lorne H. Reed
Universal Seismic Surveys, Ltd.
223 14th St. N.W.
Calgary, Alberta
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City

Chartered September 30, 1952
Pres.: John Bemrose
1st V-Pres.: W. B. Robinson
2nd V-Pres.: D. D. Moore
Treas.: Ben W. Smith
Secty.: George E. Anderson
Stanolind Oil & Gas Co.
Box 1654
Oklahoma City, Oklahoma
Meetings: Monthly, 2nd or 3rd Monday
Time and place to be announced

Casper Geophysical Society

Chartered May 23, 1953
Pres.: Homer E. Roberts
V-Pres.: Dupree McGrady
Secty.: R. L. Billings
Forest Oil Corp.
254 N. Center St.
Casper, Wyoming
Meetings: Monthly, 1st Monday
7:00 P.M., dinner ($2.75)
Townsend Hotel
Casper, Wyoming

Geophysical Society of South Texas

Chartered November 9, 1953
Pres.: W. Lee Moore
V-Pres.: William R. Gray
Secty.: Dillon S. Frazier
Petty Geophysical Engg. Co.
Transit Tower
San Antonio, Texas
Meetings: 1st and 3rd Wednesdays
Noon luncheon, Sommers Cafeteria
Main Plaza, San Antonio

Southeastern Geophysical Society

Chartered April 1, 1954
Pres.: Merrill Smith
V-Pres.: R. E. Sheriff
Secty.: G. F. Berry
203 Carondelet Bldg.
New Orleans, Louisiana
Meetings: Monthly, 3rd Monday
Noon luncheon ($1.50)
St. Charles Hotel
New Orleans

Montana Geophysical Society

Chartered April 12, 1954
Pres.: Sam Marsh
1st V-Pres.: Jack Peters
2nd V-Pres.: M. D. Wickerham
Secty.: C. F. Moore
Sohio Petroleum Company
Box 2558
Billings, Montana
Meetings: Monthly, 2nd Monday
7:30 P.M., Billings Petroleum Club
Billings, Montana

Jackson Geophysical Society

Chartered May 12, 1955
Pres.: Fred Forward
V-Pres.: W. J. Robinson
Secty.: R. Long
Stanolind Oil & Gas Co.
1166 Raymond Road
Jackson, Mississippi
Meetings: Monthly, during 3rd week
5:30 P.M., refreshments
6:30 P.M., dinner ($2.00)
Roof Garden of Robert E. Lee Hotel
Jackson, Mississippi

Southwest Louisiana Geophysical Society

Chartered January 4, 1956
Pres.: John W. Bell, Jr.
1st V-Pres.: A. V. Hargis
2nd V-Pres.: W. W. Daly
Secty.: Lawrence N. Ott
Tidewater Oil Co.
Box 1147, OCS
Lafayette, Louisiana
Meetings: to be announced

Dakota Geophysical Society

To be chartered
Pres.: W. E. Phillips
1st V-Pres.: Hugh McCain
2nd V-Pres.: Quin Hayes
Secty.: R. R. Phair
Roundup Powder Company
Box 452
Bismarck, North Dakota
Meetings: Monthly, 1st Friday
7:30 P.M., Petroleum Club
Prince Hotel
Bismarck, North Dakota

Utah Geophysical Society

Chartered October 29, 1956
Pres.: T. E. Hobbs
1st V-Pres.: J. R. Cheney
2nd V-Pres.: K. L. Cook
Secty.: John W. Erwin

STUDENT SOCIETIES

(Affiliated)

Colorado School of Mines Society of Student Geophysicists

Secty.: John M. Perrigo
Department of Geophysics
Colorado School of Mines
Golden, Colorado
Meetings: to be announced

Geophysical Society of Saint Louis University

Secty.: Thomas McEvilly
Saint Louis University
3621 Olive Street
St. Louis 8, Missouri
Meetings: Monthly, 2nd Wednesday
7:30 P.M., meeting only
Institute of Technology

SEG Houston Student Section

Secty.: James A. Sherar
3618 Overbrook
Houston, Texas
Meetings: to be announced

University of Toronto Geophysical Society

Secty.: John E. Hogg
49 St. George Street
Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursdays
4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society

Secty.: Vernon Malahy
Department of Geophysics
600 South College
Tulsa, Oklahoma
Meetings: Weekly, Thursday
4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section

Secty.: John T. Sample, Jr.
Box 56
Texas Western College
El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society

Secty.: James B. Imswiler
College of Mineral Industries
University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society

Secty.: Howard L. Confer
College of Mines and
Mineral Industries
Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday
Noon, Mines Building
Other special meetings to be announced

Georgia Institute of Technology, Geophysical Society

Secty.: William Hogarth
Box 4748
Atlanta, Georgia
Meetings: to be announced

A & M College of Texas Student Geophysical Society

Secty.: Robert T. Smith
Geology and Geophysics Dept.
A & M College of Texas
College Station, Texas

MEMBERSHIP APPLICATIONS RECEIVED

Applications for Active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

H. R. Adair (R. F. Weichert, C. N. Hurry, R. C. Clark, C. J. Quinn)
William Hoyt Cox (Richard H. Hopkins, Robert L. Henson, W. E. Hollingsworth, George A. McCalpin)
Alexis de Spengler (Michel Tenailie, Curtis Johnson, J. J. Burger, R. H. Gees)
James N. Elliott (John F. Boyd, J. B. Ferguson, Ray St. Germain, E. E. Jones)
O. A. Erdman (S. G. Pearson, R. B. Ross, R. J. Copeland, R. H. Carlyle)
Jodie C. Fulton (R. H. Dana, J. N. Morehead, G. J. Long, John R. Harmonson)
Sigemasa Furuya (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Joe Gaines, Jr. (S. A. White, E. I. Grizzell, R. C. Wilber, F. E. Kisler)
D. J. Hall (L. G. Morris, J. W. Hammond, H. C. Bickel, G. E. Blackledge)
Masami Hayakawa (Kumiji Iida, Shigetoshi Kirihara, H. A. Sears, J. W. Horn)
C. D. Hier (H. M. Thralls, R. F. Bennett, J. C. Hollister, W. H. Courtier)
Kiyoshi Hirasawa (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Emmett P. Horn, Jr. (C. G. McBurney, R. D. Arnett, D. M. Denton, Jr.)
Shoji Iwasaki (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Seikichi Kamata (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Tetuichi Kaneko (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Takeshi Kawashima (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Iqbal Ahmed Khan (T. A. Pezarro, J. W. Cruickshank, A. A. Fitch, J. V. S. Narayana)
L. Martinez I. (Vincente Binetti, Salvador A. Berros, Rodolfo Hernandez, Rodolfo Martin)
G. B. Matthews (G. E. Olson, J. P. Duncan, C. B. Scott, George Perkins)
Jack L. Meuschke (G. E. Andreasen, I. Zietz, R. W. Bromery, R. G. Henderson)
Kiyoshi Mori (Kumiji Iida, Shigetoshi Kurihara, H. W. Sears, J. W. Horn)
I. A. Mumme (E. Rudd, Prof. Alderman, D. Mawson, G. Aitchison)
Carl Nance, Jr. (M. H. McKinsey, H. C. Maliphant, C. D. Bearden)
N. C. O'Halloran (F. Jefferies, W. J. George, D. J. Germain-Jones, P. E. Kent)
James D. Parsley (Kenneth E. Hunter, H. V. W. Donohoo, R. W. Whipple, Duane O. Wood)
Noel Pauletto (Rene Saint, Robert David, Rene Thiers)
Carol A. Salassi (George O. Morgan, C. S. Fleischmann, W. B. Duty, Leo A. Markley)
Konosuke Sato (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Etsuzo Shima (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
Hiromu Sima (Kumiji Iida, Shigetoshi Kurihara, H. A. Sears, J. W. Horn)
H. Cecil Spicer (James R. Balsley, Jr., Irwin Roman, Harold M. Mooney, Henry R. Joesting)
Fred E. Stapleton (Robert H. Ray, Robert S. Duty, Jr., J. C. Pollard, Norman P. Teague)
Renato Trudu (A. Belluigi, C. Morelli, M. A. Boccalery, T. Rocco)
George M. Turk (H. L. Brewer, A. J. Farando, J. F. Thompson, Marvin Romberg)
Samuel F. Turner (Walter N. White, V. T. Stringfield, Harvey L. Drew, H. N. Wolcott)
James R. Vetters (Stefan Von Croy, D. F. Jewell, Jr., T. J. Thomas, R. W. Teipel)
Maurice H. Wallace (Paul Tucker, Raoul Vajk, Rudolph Weichert, Jr., Frank Rollings)
John C. Whitaker (Kenneth Hunter, H. V. W. Donohoo, Raoul Vajk, Duane O. Wood)
S. W. Williams, Jr. (M. B. Smith, M. L. Parke, J. C. Colvin, David G. Koppel)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

Hinds Agnew (F. A. Hale, Wm. P. Ogilvie, R. B. Oldaker)
Michael Alexander (John C. Hollister, R. E. Watson, Leo A. Markley)
Richard O. Beightol (J. M. Kendall, Merrill Smith, J. D. Keese)
W. D. Black (Cecil H. Green, C. M. Moore, Jr., Ray H. Wright)
Harrison L. Blair (C. A. Willner, Phil Garrison, Marvin Hewitt)
J. R. Bozman (T. G. Arnold, Tom King, Delbert Thomas)
Robert R. Brooks (Ralph C. Holmer, George R. Rogers, John C. Hollister)
Frank B. Coker (R. A. Peterson, Flint Agee, L. A. Martin, B. W. Sorge)
Leendert DeWitte (L. Y. Faust, H. G. Doll, John C. Stick)
Earl G. Ellis (George O. Morgan, J. B. Meitzen, A. P. Wendler)
W. T. Langstroth (R. W. Gemmer, S. R. Marsh, H. M. Buckner)
Loring O. Lee (Cecil Green, C. M. Moore, Jr., V. J. Chaput, J. L. Stephens)
Murdo MacIver (H. J. Kidder, D. V. Bigelow, L. Castelli, R. H. Brooks)
Richard F. Moyse (R. B. Ross, S. G. Pearson, R. J. Copeland)
Robert W. Nordling, Jr. (D. A. DeWoody, J. W. Texter, J. E. McGee)
V. K. Poland (L. E. Twining, R. L. Palmer, W. H. Reese)
Harold E. Province (S. W. Totten, M. G. Frey, J. C. MacGregor)
Richard F. Quinn (S. A. White, N. N. Zirbel, A. W. Bunsen, G. B. Clark)
Laney G. Reed (R. F. Bennett, E. M. Peacock, J. J. Schneider)
Eugene T. Schnieder (W. T. Buckingham, J. W. Anderson, F. J. DiGiulio)
Leon E. Tabor (F. F. Campbell, A. E. McKay, Richard Brewer)
Thomas M. Tullis (Robert Dyk, F. E. Romberg, Richard Geyer, J. C. Hollister)

COMMITTEE CHAIRMEN
FOR THE
TWENTY-SIXTH ANNUAL MEETING
SOCIETY OF EXPLORATION GEOPHYSICISTS

C. W. PENNY
General Geophysical Co.
Vice-Chairman

J. A. HARRIS
California Company
Exhibits

O. G. HOLEKAMP
Shell Oil Company
Technical Program

L. W. COBENA
The Texas Company
Housing

MERRILL SMITH
The Texas Company
Finance

JOHN F. BOYD
Tidelands Exploration Co.
Registration & Reception

NEIL W. MANN
Geophysical Service Inc.
Arrangements

GERRY BURTON
Shell Oil Company
Publicity

D. D. UTTERBACK
Freeport Sulphur Co.
Entertainment

R. E. HALSEY
Sinclair Oil & Gas Co.
Program Publication

ALLENE BOYD
Ladies Program

MEETINGS

TWENTY-SIXTH ANNUAL MEETING

Roosevelt Hotel, New Orleans, Louisiana

October 29–November 1, 1956

Members of the Southeastern Geophysical Society, New Orleans, were hosts to the SEG during its 26th Annual Meeting. Kenneth R. Wells, general chairman, and C. W. Penny, vice-chairman, directed plans and arrangements; John F. Boyd, president of the Southeastern Geophysical Society, served as chairman of the registration and reception committee.

KENNETH R. WELLS
GENERAL CHAIRMAN
26TH ANNUAL MEETING

JOHN F. BOYD
PRESIDENT, SOUTHEASTERN
GEOPHYSICAL SOCIETY

In appreciation:

On the preceding page are pictures of the chairmen of the committees for the 1956 Annual Meeting. The success of this meeting was due largely to the splendid cooperation and the efforts of these people and their committee members. My sincere thanks to the various companies who have allowed their employees to give time and effort to convention affairs.

We had an excellent technical program and are grateful to the authors for their contributions.

Without the exhibitors, who largely support the convention, it would not be possible to hold it in the established style. Our appreciation can be shown by patronizing them wherever practicable.

The executive committee of SEG have been most helpful in their counsel and assistance, and a sincere vote of thanks is due Colin Campbell and the business office of the Society for the assistance given us. Without their help our task would have been much more difficult.

A special word of thanks is due Mr. R. E. Sheriff and Mr. John Bemrose for their assistance on the program committee and to Mr. E. H. Shannon who served as the housing chairman during most of the convention planning and resigned upon his transfer to another city.

The Reverend Doctor Victor J. Blum (left), Dean of the Institute of Technology, Saint Louis University, received the student essay awards for two of his students, Thomas V. McEvilly (first prize) and Emil J. Mateker, Jr. (third prize) from F. J. Agnich, chairman of the student membership committee.

The European Association of Exploration Geophysicists was well represented at the 26th annual meeting. The photographer did not get their names. Greetings from EAEG were conveyed at the opening session by Ir. A. Van Weelden, its founder and first president (second from right on the first row).

The Shell Oil Company very generously contributed the use of their publicity department to publicize the meeting, and they did an outstanding job.

KENNETH R. WELLS
General Chairman

Statistics:

A total of 1,553 members and guests were registered, and 1,329 paid the $5.00 fee. The 224 non-paying guests included 98 exhibits personnel, 96 ladies, and 30 students. Over 1,200 hotel rooms were occupied by the delegates. Because no formal registration was held for the ladies the exact number attending cannot be determined, but it is estimated 500 ladies were present. Social functions were well attended, but not over-crowded, and 139 went on the offshore field trip.

ANALYSIS OF REGISTRATION BY POSITIONS

Management		**331**
Board chairman	2	
Director	7	
Partner	19	
President or owner	88	
Vice-president	80	
Secretary or treasurer	9	
Department manager	124	
Exploration	16	
Personnel	1	
Other (not specified)	107	
Independent oil producer	2	
Operations		**763**
Geophysical supervisor	126	
Seismologist	49	
Chief geophysicist	37	
Geophysicist	329	
Chief interpreter	8	
Interpreter	1	
Party chief	73	
Computer	47	
Observer	3	
Magnetometer chief	1	
Gravity department	1	
Draftsman	2	
Consultant	17	
Geologist	67	
Operations	2	
Sales		**101**
Sales manager	58	
Service man	2	
Representative	7	
Engineer	12	
Other (not specified)	22	
Research		**127**
Physicist	25	
Professor	11	
Mathematician	2	
Designer	2	
Engineer	87	
Research	39	
Chief	6	
Field	9	
Safety	4	
Electronic	3	

Officer s of the Society who were present at the meeting: (Left to right) Doctor Norman Ricker, who is now completing the second year as editor; Roy F. Bennett, president; Doctor J. P. Woods, vice-president; and Professor John C. Hollister, secretary-treasurer. Robert C. Dunlap, Jr., past president, was unable to attend because of illness.

Morgan J. Davis, a former president of the American Association of Petroleum Geologists, was a featured speaker.

Development	3		
Project	3		
Testing	2		
Instruments	2		
Electric cable	1		
Other (not specified)	15		
Miscellaneous			**231**
Editor		3	
Student (total of 30 registered as students)		4	
Well logging coordinator		1	
Network chief		1	
Claim agent		1	
Ladies (about 500 were present)		96	
No position listed		125	
Total Registration			**1,553**
Paid		1,329	
Unpaid		224	
Exhibitors	98		
Ladies	96		
Students	30		

Program:

Abstracts of the 50 papers presented and 9 which were read by title appear elsewhere in the *Society Round Table*. The technical program opened at 2:00 o'clock Monday afternoon, October 29, and closed at 5:00 o'clock Thursday afternoon, November 1.

Robert C. Dunlap, Jr., outgoing president of the Society, was unable to attend the meeting because of an illness. At this writing Mr. Dunlap had recovered quite well from the effects of a delicate spinal operation. In his place Mr. Dave P. Carlton, vice president, presided and conveyed Mr. Dunlap's greeting and best wishes to the delegates present at the opening session. On invitation from the Society, Dr. Paul E. Klopsteg of the National Science Foundation described the growth in size and recognition of the American Institute of Physics. H. G. Patrick presented the report of the geophysical activity committee covering 1955 and the first half of 1956. These reports appear in the January, 1957 issue of GEOPHYSICS. Another invited speaker on the opening session was Dr. F. H. Lahee, past president of the American Association of Petroleum Geologists, and formerly chairman of the AAPG committee on exploratory drilling. Dr. H. F. Dunlap presented the report of the SEG research committee entitled "Geophysical research and progress in exploration," co-authored by Dr. Milton B. Dobrin.

A featured address of the meeting was given by Mr. Morgan J. Davis, past president of the American Association of Petroleum Geologists. His paper, "Geophysics—full partner," appears in this issue of GEOPHYSICS.

Invited papers on the International Geophysical Year were presented by Mr. Hugh Odishaw, executive secretary of the IGY, U. S. committee; Dr. Perry Byerly, SEG member on the U. S. committee; and Dr. J. Allen Hynek, who is in charge of the IGY satellite tracking program.

Annual business meeting:

The *Annual Report*, comprising detailed reports by all officers and committees of the Society, was distributed to all delegates at registration. During the opening session vice president Carlton called attention to the printed reports, noting some modifications ordered by the council and requesting comments from the members present. The reports were received as modified on vote of the members. Then Mr. Carlton introduced the newly-elected officers: Roy F. Bennett, president; J. P. Woods, vice-president; and John C. Hollister, secretary-treasurer. He announced that Norman Ricker would continue in his second year as editor. The Annual Business Meeting was adjourned at 5:00 o'clock. The Annual Report appears in GEOPHYSICS, January 1957 issue.

Doctor Raymond A. Peterson (left) received the best paper award for a paper which he co-authored with W. R. Fillippone and F. B. Coker, from vice-president Dave P. Carlton.

Doctor L. L. Nettleton (right) received the eleventh award of honorary membership from Doctor Nelson C. Steenland, who presented the citation.

Social functions:

Because the "charms of old New Orleans" were available to the members, elaborate social gatherings were not planned. On Monday evening the Society sponsored a "Get-aquainted cocktail party," and similar functions were sponsored jointly by a group of operating companies on Tuesday and Wednesday evenings. On Tuesday evening approximately 400 of the delegates enjoyed a boat ride on the famous river steamer *President* which had been chartered especially for the meeting. The annual dance was held Wednesday night in the grand ballroom of the Roosevelt Hotel, with music by Jan Garber and his orchestra.

Ladies' entertainment:

The attractions of New Orleans brought more than the usual number of ladies to the meeting, and the ladies' entertainment committee under the chairmanship of Mrs. John F. Boyd (Allene) chose the "Old South" as their theme in planning several events. On Monday the ladies enjoyed a morning walk through the "Vieux Carré," and in the afternoon toured the garden district of New Orleans. The one planned event for Tuesday was a Mardi Gras luncheon at the Jung Hotel. A sherry party in the famous Court of Two Sisters was held Wednesday afternoon. Throughout the meeting coffee and doughnuts were served the ladies in the University Room of the Roosevelt Hotel.

Field trip:

The unusual conditions under which geophysical work is carried out in the marshes of southern Louisiana and offshore in the Gulf of Mexico were experienced by 139 "landlubbers" and other geophysicists whose feet are not webbed. Most of the delegates saw for the first time how marsh buggies, river boats, piroques, helicopters, shooting boats and recording boats are used. After travelling by busses through the marshy "Cajun country" to Grand Isle, the group boarded small boats which took them out into the Gulf where a seismic water shooting demonstration was featured. Several offshore drilling platforms were seen, some in various stages of construction, and others in full operation. Perfect weather and a calm sea added much to the enjoyment of the trip, and several contract companies and producing companies showed typical southern hospitality in providing transportation and other facilities.

Awards:

Honorary membership, the highest award of the Society, was conferred upon L. L. Nettleton who became the eleventh geophysicist so honored in the Society's 26 years. The citation by N. C. Steenland follows this article in the Round Table section. Also during the opening session the awards in the annual student essay contest were made by F. J. Agnich, chairman of the student membership committee. First prize of $150 went to Thomas V. McEvilly, a student member of the Society and a graduate fellow in engineering geophysics at Saint Louis University. Mr. McEvilly is also a member of the Saint Louis University Geophysical Society. The title of his paper is "Abnormal sedimentary susceptibilities in eastern Missouri." The second prize of $100 was won by Ronald E. Diederich, a member of the Colorado School of Mines Society of Student Geophysicists and a senior in geophysical engineering. His paper is entitled "A review of the Rayleigh wave." The third prize of $50 went to Emil J. Mateker, Jr., graduate student in geophysical engineering at Saint Louis University and a member of its student section of SEG. The title is "Gravity survey of the Cap Au Gres structure in the Brussels-Hardin quadrangle, Illinois." The Rev. V. J. Blum, S.J., Dean of the Institute of Technology at Saint Louis University, received the awards for Mr. McEvilly and Mr. Mateker. Professor John C. Hollister of the Colorado School of Mines received the award for Mr. Diederich.

The Best Paper Award went to R. A. Peterson, W. R. Fillippone and F. B. Coker for their paper, "The synthesis of seismograms from well log data," published in the July, 1955, issue of GEOPHYSICS. The bronze plaques and certificates were received for the authors by Dr. Peterson.

Mr. Agnich also announced that two scholarships in geophysics, each for four years in the amount

Delegates from foreign countries included these four members of the newly-formed Venezuelan Geophysical Society in Caracas: (Left to right) Harvey Pless, E. J. Assiter, Benny McKee and John Wright.

Two southern belles, Mrs. D. D. Utterback (left) and Mrs. John F. Boyd, were hostesses for a patio party in the Court of Two Sisters which climaxed the program of ladies' entertainment on the "Old South" theme.

of $3,000, were awarded through the student membership committee. The Mayhew Scholarship, sponsored by the Mayhew Supply Company of Dallas, Texas, was granted to Richard F. McReynolds, son of P. T. McReynolds, engineer for Humble Oil and Refining Co., Brownfield, Texas. Young McReynolds has enrolled in geophysics at the Colorado School of Mines.

The Griffin Scholarship, sponsored by the Griffin Tank and Welding Service of Dallas, Texas, was won by Ramil C. Wright, son of Ronald E. Wright, seismic supervisor for General Geophysical Company, New Orleans. He has enrolled at The Rice Institute, where he is now studying geophysics.

The Hawthorne Scholarship in Geophysics was announced at the meeting. Sponsored by Herb J. Hawthorne, Inc., it provides for one scholarship in the amount of $750 for one year for a student of physics, geophysics or engineering leading toward geophysical work in an American university. An additional $700 per year has been set up by Hawthorne for a scholarship in a Canadian university through the Canadian Society of Exploration Geophysicists, Calgary Section of SEG.

Exhibits:

A total of 46 companies exhibited during the four days of the meeting, occupying 58 booths and areas in the International Room of the Roosevelt Hotel. These exhibits were open to delegates from 9:00 A.M. to 6:00 P.M. The Society did not arrange space for outdoor exhibits since there was none available within reasonable distance of convention headquarters. The exhibits committee added a new service to exhibitors in supplying daily attendance rosters giving name, position, company, mailing address and hotel room number of each registered delegate. Free exhibit space was provided the American Association of Petroleum Geologists, the American Institute of Physics and the Houston Students Section of SEG.

Automatic data plotting equipment and magnetic recording of seismic signals held the most prominent place during this exhibit, with several companies choosing the SEG meeting as the time to announce their most recent developments. Working models and prototypes were demonstrated, and one delegate was heard to remark that he found quite as much new information in the exhibit as he did during the technical sessions.

SOCIETY OF EXPLORATION GEOPHYSICISTS

26TH ANNUAL MEETING

CLASSIFICATION OF EXHIBITORS

14	manufacturers of geophysical instruments
7	manufacturers of geophysical field equipment (2 cable manufacturers, 2 drilling rig builders, 2 drilling bit manufacturers, 1 portable field camp fabricator)
6	geophysical survey contractors
4	explosives manufacturers
4	distributors of geophysical instruments, supplies and parts
3	scientific societies (publishers)
3	aerial photographic survey contractors
2	manufacturers of photographic recording papers
1	helicopter rental contractor
1	manufacturer of drilling muds
1	manufacturer of light trucks
46	total

ELEVENTH AWARD OF HONORARY MEMBERSHIP

CITATION

The Society is privileged to honor Dr. Lewis Lomax Nettleton with its eleventh honorary membership. Such an honor could not be more appropriate, for here we have a pioneer of the geophysical industry and a bulwark of our own Society which he has served most actively for more than twenty years. Known as the "man who wrote the book" or as "Mr. Salt Dome," he personifies our profession and may aptly be called "Mr. Geophysics."

Dr. Nettleton was born in a small town of western Idaho, Nampa, on June 24, 1896. His undergraduate courses were completed at the University of Idaho with a Bachelor of Science degree in physics in 1918. Subsequently he received further degrees in physics at the University of Wisconsin, a Master of Science in 1921 and a doctorate in 1923. While at Wisconsin, he was an assistant on the staff of the physics department.

With the completion of his formal education, he began his professional career as a physicist in the research department of the Union Switch and Signal Company in Pittsburgh. Patent applications reveal his developing apparatus for railway-traffic-control during this period.

The year 1928 found Dr. Nettleton embarking on his geophysical career with Gulf Research and Development Co. where he afterwards became chief of the gravity section. In an amazingly short time he published, in 1934 actually, his concept of the genesis of salt domes, "Fluid mechanics of salt domes," a concept which is fundamental to and of profound influence upon the entire general subject of structural geology as well as the more restricted field of geophysical prospecting. During continued service with Gulf he quite quickly developed fluid models illustrating the growth of salt domes by reason of the relative buoyancy of a substratum of salt of lower density.

Dr. Nettleton's ability to think with originality and clarity is manifested in his publications. His geophysical papers led directly to his departure from Gulf in 1946 to become a partner in Gravity Meter Exploration Company of Houston, Texas. Dr. Schumacher had resigned his partnership. The two remaining partners, Mr. Pagan and Mr. Saville, simply began reading geophysical literature to find a candidate for their new technical partner, and their search ended in the selection of Dr. Nettleton. He has remained in the capacity of a partner in GMX until this time.

Dr. Nettleton's contributions to our profession extend far beyond his great commercial successes into the scientific backbone of geophysics by reason of his very significant publications and his great service to our Society. His writing ability served us in great stead during 1945, 1946, and 1947 when he was our editor. By way of further service, the Society elected him vice-president in 1947 and president in 1948.

The publication that has made him an acquaintance of all of us in our very embryonic stage is his textbook, *Geophysical prospecting for oil*, published in 1940. Of next pre-eminence are his articles on the genesis of salt domes, the 1934 paper which presented the hypothesis and the 1943 paper which describes the model experiments of salt dome flowage. Dr. Nettleton has also published significant papers concerning the reduction of data, the calculations of gravity and magnetic fields, and the general subject of residual anomalies.

You have perhaps noted Dr. Nettleton's successful application of physics to geologic problems. Perhaps his most unusual achievement is this mastery of geology. Without having had any formal training in geology, he has served the Geological Society of America for three years as a member of its projects committee, the committee which screens the applications for funds for research projects. In addition he has been one of four civilian members on the panel on geology, of the committee on geophysical sciences of the Defense Department's Research and Development Board. These facts illustrate his never-ending effort to correlate geophysics and geology—to use geophysics as a geologic tool.

The outstanding factor in his career is his insatiable curiosity, and great intellectual power—scientifically trained. This ability and curiosity have influenced all geophysicists and will continue to influence all future geophysicists, because it is a mark of his greatness that his spoken and written

words are words of truth. Such is the product of a fine mind placed in a man of supreme moral and intellectual honesty. Such is a man upon which our very profession is based.

This is a great moment for the Society, for Dr. Nettleton, and for the speaker who is simultaneously experiencing great humility and honor in bestowing the Society's eleventh honorary membership on Dr. Lewis L. Nettleton.

NELSON C. STEENLAND

ABSTRACTS OF PAPERS PRESENTED OR READ BY TITLE AT THE TWENTY-SIXTH ANNUAL MEETING

NEW ORLEANS, LOUISIANA, OCTOBER 29–NOVEMBER 1, 1956

Physics in America and the AIP

PAUL E. KLOPSTEG

For the complete paper see GEOPHYSICS, *January, 1957 issue.*

The part played by statistics in exploration

FREDERIC H. LAHEE

In the business of exploring for oil and gas there are many factors to be considered. Such are the cost of drilling (including accessibility, availability of materials, depth to expected pay, etc.), markets, probable size of reserves for profitable exploitation, legal restrictions, tax angle, regional geology, local geology, and so on. To these, which are more commonly considered, should be added the statistical record. Statistics imply the tabulation and comparison of accumulated classified data. Therefore, statistics cannot be applied until after there has been considerable experience in an area, but as soon as this condition has been reached, selection of areas for further exploration may well be guided by the statistical background of the past.

Geophysical research and progress in exploration

MILTON B. DOBRIN and HENRY F. DUNLAP

For the complete paper see GEOPHYSICS, *this issue.*

Geophysics—full partner

MORGAN J. DAVIS

For the complete paper see GEOPHYSICS, *this issue.*

Geology and geophysics of the Gulf of Mexico

PAUL L. LYONS

Integration abstract of the presently known geology and geophysics of the Gulf of Mexico assists in the eventual solution of the many problems of tectonics, sedimentation, and basin formation which are yet unanswered. The greatest problem is the geologic section existing in the central part of the Gulf basin. This large basin may be regarded as centering at the position of a great gravity maximum. Patterns of thrusting, graben structures, volcanic vents, salt basins, and tension faults are evident. Sedimentation has been controlled mainly by the ever present Mississippi River, and sand distribution has been controlled by successive positions of the shore line and the river. A theory of origin and development is presented.

A review of Pacific Coast offshore seismic methods

CARL H. SAVIT

The steep dips of California geology demand cross control at every shot point. This requirement determines almost all of the techniques used in Pacific Coast offshore work. Surveying methods

have been devised to determine the exact configuration of each spread layout at the moment of detonation of the shot. Data reduction methods include dip resolution for each reflection and projection of the reflections into the plane of the cross section. This procedure also facilitates the detection and identification of the many reflected refractions encountered.

Varying water depths produce problems ranging from wave guide resonance to multiple reflections of high order. Computing and plotting techniques are designed to identify the multiple reflections and thus to distinguish them from the desired simple reflections.

Several records and a cross section are presented to illustrate some of the problems discussed.

Future offshore oil provinces of the world

T. R. GEODICKE

Modern exploration techniques, including concentrated use of geophysics, are being applied with a great deal of success to the location and development of marine oil resources in the Gulf of Mexico. A ratio of one producer in two and one-half marine wells drilled in the Gulf has directed the attention of oil men to similar areas in the world, where large quantities of petoleum may lie beneath shallow seas.

Some of the following areas are expected to be focal points of interest for exploration: In the Americas; the Gulf of Mexico and Caribbean coastal areas of Cuba, Central America and South America; also shelf areas off Ecuador and Peru. Europe and the Near East will see development along the Atlantic coast of France, on shelf areas in the Mediterranean and especially in the Persian Gulf, where a marine oil field is producing at the present. Exploration and development in Asia will be centered on the extended marine areas of the Indonesian archipelago as well as on shelf areas along the coast of Pakistan, Iran, India and Burma. Marine oil possibilities will also be investigated in the Philippines and along the west and northwest coast of Australia.

Analysis of offshore domes from gravity surveys

L. L. NETTLETON

This paper reviews the effectiveness of gravity surveys for determining shape and depth of offshore salt domes and is illustrated with gravity maps and cross sections from two examples.

The San Luis Pass dome, about 10 miles offshore and between Freeport and Galveston was covered with a very detailed gravity survey of some 130 stations for the determination of the location, depth and thickness of caprock in advance of drilling to evaluate the dome as a sulphur prospect. The gravity survey and its interpretation indicated a shallow dome and outlined a large area with moderate thickness of caprock. Subsequent drilling confirmed the geophysical indications quite satisfactorily.

A gravity survey of some 50 stations was made over the large topographic mound "Way," about 120 miles southeasterly from Galveston and near the edge of the continental shelf. The topography has relief of nearly 400 feet with a small area reaching to a minimum depth of about 60 feet. The gravity survey shows a large circular minimum with an indefinite indication of a central maximum. Illustrations show the gravity results, the topography and a possible structural interpretation.

Field equipment, techniques, and interpretive procedures of the offshore seismic crew

H. L. GRANT

A vast amount of oil will be found offshore by marine seismic exploration. Since 1945 major improvements in offshore operations have been achieved. These improvements include the type of boats used, new jetting and drilling techniques, and better seismic instruments such as water break amplifiers and floating cables and seismometers.

Offshore operations, on a unit basis, cost roughly one quarter the price of a land operation. Production per field man and per interpretive man is 6.5 and 3.5 times as efficient, respectively, offshore than on land.

Considering the continental shelf areas, areas now under lease, and the number of wells now completed, offshore operations are just now getting started.

Recommended practices in the handling and use of seismic explosives

T. L. McCorkle

This paper is based on a series of 35 mm. color transparencies showing typical seismic operations in Wyoming, offshore along the Gulf Coast, and in a Louisiana swamp. Emphasis is placed on the proper methods for handling and using explosives in these vastly different types of work. The author discusses the pictures as they are presented, pointing out good and bad practices, and comments on safety in general from the standpoint of an explosives manufacturer.

Design principles for seismic reflection amplifiers

A. J. Hermont

During the past two years the exploration and production research laboratory, Shell Development Company, Houston, Texas, had occasion to evaluate a number of seismic amplifier channels submitted by various seismic contractors and manufacturers. From this study, material for the present paper has been collected. Filtering is mentioned from a point of view of minimum requirements for an average reflection survey. Absolute sensitivity minimum useful signal voltage from a geophone, and noise are discussed. Gain control is treated in two regions, viz. the automatic control region and the initial control region. For the former, static and dynamic control characteristics are discussed and the factors influencing the control range are brought out. For the latter, it is pointed out when a system is said to require mandatory or optional initial suppression.

Harmonic distortion, originating in the inductive components of the input circuit due to low frequency roller energy, is presented in a manner facilitating understanding of the distribution of low frequency filtering along the channel.

Methods of filtering seismic data

Mark K. Smith

Filtering in its general sense represents an important phase of data processing. In recent years such new methods as delay line filtering and digital filtering as well as conventional seismic filtering have been described in the literature. The purpose of this paper is to clarify the relationship between these methods of filtering and to compare design criteria such as cross-correlation filtering and zero-phase filtering. Synthetic records as well as field records are used to illustrate the effects of the various filtering techniques.

Display of magnetically recorded seismic data

C. F. Hadley

A method of making multitrace seismic records using electrically sensitive paper is described. The record is immediately available for use without any type of processing. A rotating scanning disk carrying wire brushes on its periphery is revolved with its axis parallel to the direction of the motion of the paper. The electrical paper is pulled under the scanning disk. The paper is so shaped that brushes remain in contact with the paper. Short electrical pulses are fed to the brushes so as to produce a number of traces composed of closely spaced dots. The position of the dots is determined by the time of occurrence of the pulses which is a function of the amplitude of the seismic signal. Timing lines are placed on the record by feeding a series of dots to all brushes in unison. Provision is made to count down and emphasize the fifth and tenth timing lines. A system of multiplexing is used to employ each brush on many traces and thus reduce the rotational speed of the scanning disk. The frequency response is satisfactory for seismic work.

Time-depth conversion camera

E. Gordon Perry

A conventional seismic camera has been modified so that the record it produces may be in time or depth. When a depth record is required the time break trips a mechanism which will change the

speed of the paper feed drive from being linear in time to linear in depth. The start of this conversion may be delayed by a predetermined amount of take into account weathering, elevation changes, or any other time correction.

The camera will convert from a time to a depth scale according to either the relationship $V=V_0+AZ$ or $V=V_0+AT$. Other relationships may be used by changing the velocity correction cam. It is not necessary to change the cam for different values of V or A in smooth velocity relationships.

On trial conversions the greatest area measured was 8 feet at a depth of 16,000 feet.

The Gulf seismic profile printer

E. M. PALMER

The complete paper is published in GEOPHYSICS, *this issue.*

Optical analog gravity computer

R. W. BALTOSSER

The SSC optical analog gravity computer is an instrument for conveniently determining the simulated gravity response from geologic cross sections with a third dimension either finite or infinite.

Both two and three dimensional simulations may be done in variable scale ratios.

The geologic cross sections are prepared in a conventional manner with shading controlling the simulated densities.

The theory of the instrument is described, and its limitations and possibilities are discussed. Examples of gravity profiles from typical cross sections are shown.

Directivity effect of elongated charges

A. W. MUSGRAVE

After years of development it has been determined that the energy from the detonation of a low velocity explosive in an elongated column approaches a unidirectional pattern. This column is placed in the sub-weathering material extending ½ to 2 wavelengths in length depending on the frequency of energy desired.

A study of the theory of propagation showed that greater directivity can be obtained from the same length of charge by using a powder with a detonation rate less than the side wall velocity of the shot hole. The optimum velocity, between increased directivity and loss of energy of the charge, is about ⅔ of the side wall velocity.

The reduction of horizontal energy is of great value. However, examples of the effect of the elongated charges indicate that a very important effect of directivity is the elimination of "ghosts."

Interpretation may be greatly facilitated by the reduction of much of the unwanted energy on the record. Character is no longer dependent upon hole depth.

Accident facts—1955

BRIAN R. REUTER

The relative value of statistics, when applied to accident prevention, is an important part of all accident prevention programs. The tendency, however, is to accept accident facts and figures as the panacea for our accident problems; whereas accident analysis, to determine specific accident causes, is the basis for a successful accident prevention program.

Multiple reflection in offshore seismic operations

JOHN BRUSTAD

Multiples are especially troublesome in water operations because of the high reflection coefficients of the ocean floor and of the water surface. Seventh multiples, in fact, have been identified in regions covered by shallow water.

In order to prevent the mapping of non-existent structure, it is necessary to identify multiple reflections. It can be shown, using some simplifying assumptions, that the apparent angle of dip of the nth multiple is equal to the angle of the primary reflector plus n times the angle of the ocean bottom. Through the use of charts, then, it is possible to deduce the theoretical moveout of any multiple. This knowledge, together with that of the reflection time and amplitude, aids materially in identifying multiples.

In one particular case some very unusual multiples have been observed from what is believed to be a 200 feet thick layer of mud covering a hard ocean bottom. The many multiples occurring were identified by their amplitudes, times, and moveouts.

Wave propagation in a liquid layer

D. T. Liu

In many areas offshore, the conventional seismic record has the appearance of a series of sine waves or simple odd harmonic combinations of sine waves, with a fundamental wave length four times the water depth. Burg, et. al., in a ray theory treatment, ascribe this oscillatory phenomenon to guided energy traveling in the water layer.

A solution of the pressure wave equation for a point source in the water layer has been obtained. It allows one to examine not only the frequency dependence with the depth, but also the transient amplitude response with depth, range, and time.

It is concluded that in most actual situations, the phenomenon cannot be wholly explained by the assumed mechanism, because the theory indicates too rapid a decay of the energy.

On a theoretical method for identifying rock-type and obtaining shear modulus of bottom sediments in water-covered areas

E. Strick

If a seismic source such as is used in seismic exploration is utilized to excite the bottom sediments in water-covered areas, then in addition to the widely used critically refracted P-wave and the direct and reflected arrivals, there also can exist two interface waves, namely the Stoneley wave and the pseudo-Rayleigh wave. For soft bottoms which have a shear velocity less than that of the water velocity, one can determine the shear velocity, and therefore, the rigidity of the sediment from the arrival time of the Stoneley wave. For hard bottoms which have a shear velocity which is greater than the water velocity, the pseudo-Rayleigh interface wave can be used to determine the rotational velocity.

Vertical particle velocity detectors can, for elastic systems, enable a determination of the rigidity to be made over a ratio-range of ten thousand to one by means of these interface waves whose amplitude will, for common rock types, always be constant within a factor of two.

Geophysical and geological investigation of sea mounds in the Gulf of Mexico

W. E. Allen, L. Stanley and T. F. Vining

The results of a geophysical-geological expedition to the edge of the continental shelf in the Gulf of Mexico to study sea-mounds are reported. Data taken aboard the vessel *Parker* from October 20–22, 1954, around Latitude 28 09 N, Longitude 94 18 W, include: Gravity measurements taken with a LaCoste-Romberg underwater gravity meter, cores taken with a modified Kullenberg type bottom corer, depth-temperature measurements taken with a bathy thermograph, and bottom topography determined by depth recorder records. Lorac equipment was used for precise positioning of observations. The mound investigated has a relief of about 120 feet and extends 1800 feet in a NE-SW direction and 800 feet in a NW-SE direction. It is considered representative of the smaller mounds and is similar, geomorphically, to the larger mounds. Since the maximum gravity anomaly with associated rim minima developed around the mound suggests a large shallow cap rock salt dome; it is concluded that this mound owes its existence to a salt dome intrusion and this may well account for the origin of many more sea-mounds in the Texas-Louisiana area.

A refraction procedure for delineating salt domes

W. Lee Moore

The refraction method continues to be a useful tool in delineating salt domes. When, for example, the presence and outline of a dome are suspected from either reflection or gravity surveys, the center of a network of refraction profiles lines is made to coincide with the postulated center of the dome. A surface-to-surface refraction procedure is followed whereby the top of the dome is accurately outlined as to depth and shape. A series of continuous profiles from a shotpoint near the center of the salt mass with maximum shot-detector distances up to eight miles produce data from which two-dimensional aplanatic surfaces may be constructed. An interface tangent to several aplanatic surfaces in a given plane outlines the flanks of the dome to depths of 6,000 to 8,000 feet. Controlling factors for accuracy include the velocity assumption and the absence of a competent high-velocity sedimentary refractor.

Radio position fixing for exploration in Eastern hemisphere

Wilfred St. John White

The paper describes the Decca navigator system, a radio positioning device for ships, planes and land parties. The system is an American invention and was initially used for troop landings in the Normandy invasion. Since then it has been widely used under arctic, tropic and desert conditions. It differs from current U. S. practice in that unmodulated low frequency waves are used giving long ranges (250 miles) and high accuracies as reflection and refractive errors are minimized. The system features a built in electronic standard permitting highly accurate phase measurement, lane identification eliminating the need for marker buoys and automatic plotters of advanced design.

Factors affecting the accuracy of phase comparison positioning systems

B. W. Koeppel

The factors affecting the accuracy of phase comparison positioning systems are:

1. Instrumentation
2. System geometry
3. Propagation

The relative magnitude of the errors attributable to these factors will be discussed and examples of field tests will be shown.

A direct-ranging phase comparison method of radiolocation

Joseph DeLerno, Jr.

The petroleum industry has been utilizing continuous-wave phase comparison methods of radiolocation since 1952 for horizontal control of geophysical surveys in offshore areas. The systems presently in use involve three or more base stations on shore and location points must be plotted on or calculated in a hyperbolic grid. The relatively new Raydist configuration described utilizes only two base stations and the locations points can be plotted as direct ranges from these two base station positions.

Oil and oceanography

Dr. T. F. Gaskell

The science of oceanography has much in common with physics of the oil industry. Offshore prospecting methods are similar to those used to study the structure of the continental shelves and of the deep sea floor. The British refraction technique using sono-buoys may be useful in some marine geophysical work. Methods of interpretation of gravity, seismic and magnetic measurements developed by oceanographers may be applicable in oil exploration, and a better understanding of echo-sounding is allied to seismic reflection studies. The wave and current investigations are required for

designing of offshore structures, and marine biological observation and core sampling of the sea-bed are closely related to studies on the formation of oil. The oceanographer and the oil man have much in common also in being both interested in observations of physical phenomena several miles below them and the instrumental techniques developed for one will apply to the other.

Some aspects of geophysical prospecting in French territories

PIERRE MOUSSEL AND JEAN MILLOUET

This paper outlines the great effort made by French authorities, oil companies and contractors to develop the various geophysical tools for oil exploration and obtain better quality data. After a brief review of the past years, perspectives for the future are presented. Special difficulties due to rough conditions in certain areas are considered and emphasis is placed on some techniques not common in the Western Hemisphere. Applications to mining problems are mentioned.

Model studies of salt-dome tectonics

TRAVIS J. PARKER

A large number of models of salt domes were constructed and analyzed in accordance with theory of scale models. The force causing the upward growth of the model domes was produced by the contrast in the densities of the materials. Single domes were initiated by a variety of methods, and flowage of material into a dome produced a peripheral sink which in turn caused the initiation of a group of "secondary domes" about the outer margin of the sink.

The diameters of the model domes were approximately equal to the thickness of the source layer from which they were developed. Layers of overburden above the core were arched and broken by normal faults, and grabens over the centers of many domes occurred as a result of the greater uplift of marginal fault segments. Radial faults were numerous. The fault patterns in the models were controlled by the size and shape of the core, the depth of the core beneath the faulted layer, the amount of uplift of that layer, the configuration of the peripheral sink, and the physical properties of the overburden.

A seismic model with six detectors

H. O. WALKER, JR.

Most seismic model investigators use a single detector and a photographic technique involving multiple exposures to obtain multiple trace pictures which are similar to conventional seismic records.

In this paper a method is described using six detectors instead of one and by means of an electronic switch the six detector outputs are displayed simultaneous,y on a single beam cathode-ray oscilloscope. Travel times and step out times can be measured and wave types identified directly on the face of the oscilloscope. For illustrative purposes, six traces can be photographed with only a single exposure.

Signals in the model contain frequencies from 2 kc to 200 kc and shot transducer repetiton rates can be 100, 200, or 1,000 per second. Suitable block diagrams are included along with an explanation of the technique involved.

Diffraction from wedges

W. L. ROEVER

Laboratory experiments have been performed to observe the diffraction of spherical pulses by the edge of a solid wedge imbedded in a fluid. The pulse is generated by a spark and the pressure field in the vicinity of the edge is mapped using a small probe. Three different diffraction fronts are observed in the fluid. The first is excited by the direct wave in the fluid, the second by the critically refracted longitudinal wave in the solid, and the third by the Stoneley or interface wave.

The results indicate that under favorable conditions at least the first type of diffraction might be observed on field seismograms.

Seismic model study of the phase velocity method of exploration

FRANK PRESS

The complete paper is published in GEOPHYSICS, *this issue.*

A model study of bubble dynamics in offshore seismic exploration

W. C. KNUDSEN

A model study of the behavior of an explosion bubble was carried out to determine the effects of different boundary conditions. The motion of the bubble was recorded with a high-speed camera. A description of the apparatus is given, and the high-speed films are shown.

Analog studies of induced polarization effects over a layered earth

CHARLES ZABLOCKI

An analog computer has been designed for use in the interpretation of induced polarization data. The model simulates the resistivity and dielectric constant of a layered earth. In this application the potential function satisfies Laplace's equation, and so an approximate solution can be obtained by means of an appropriate resistance network. This is accomplished by the conversion of Laplace's equation to finite difference form, which, in turn, is represented by an electrical circuit. The model is that of an overburden of unit thickness with an infinite substratum. Capacitor networks are paralleled with the substratum to simulate the dielectric constant of the earth. Different ratios of resistivity and dielectric constants between layers are used, a square wave is applied at the surface of the model, and the transient response is photographed from the trace displayed on an oscilloscope for different probe spacings. These curves are then interpreted in the same manner as induced polarization measurements made in the field.

The International Geophysical Year

HUGH ODISHAW

The International Geophysical Year is undoubtedly one of the most significant scientific undertakings in the history of man. For a period of a year and a half, beginning July 1, 1957, thousands of scientists from many nations will be making simultaneous observations of the earth's interior, its crust and oceans, of the complex atmosphere reaching from the surface to heights of several hundred miles, and of the sun, which virtually controls life and events on our planet. At the present time 46 nations are participating in the International Geophysical Year and still more are expected to take part. From these scientific observations, using the world as the laboratory, will come knowledge of inestimable value to mankind.

The International Geophysical Year was conceived by the scientists of many nations through their principal international organization, the International Council of Scientific Unions (ICSU), the planning and international coordination of the scientific effort being carried out by a special committee established by ICSU in 1952, called the Comité Spécial de l'Année Géophysique Internationale (CSAGI).

Seismology and gravity in the IGY program

PERRY BYERLY

The seismological program contains: 1) Establishment of some 24 seismographic stations, principally in out-of-the-way places including polar regions and ocean islands. 2) Seismic exploration with the use of explosions in order to get the depth of the Mohorovicic discontinuity: a) at sea; b) along continental shelves; c) in South America; d) in the Antarctic to get the thickness of ice. 3) Strain measurements in South America.

The gravity program includes: 1) Pendulum observations in South and Central America, Pacific Islands, Arctic and Antarctic. 2) Gravimeter observations in the Arctic and Antarctic including ice

floe stations. 3) Underwater gravimeter measurements on the sea bottom on continental shelves and pendulum measurements in submarines around the world. 4) Earth tide measurements around the world.

Technical aspects of earth satellite tracking and their geophysical applications

J. Allen Hynek

The astrometric problem presented by the satellite and its relation to geodetic studies are treated. Instrumentation now under construction is functionally described and related to the geophysical aspects of the satellite. Methods of data reduction, accuracy of measures, and their correlation with geodetic quantities are discussed. Dissemination of satellite observations to responsible scientific groups is planned. Possible future applications of satellite data to geophysical problems are sketched.

The use of gravity surveys to determine possible fault trends

Lawrence S. Morrison

It is generally believed that most of the large simple anticlines in oil producing areas of the U. S. have been found. This implies that the search for more complex types of traps such as fault traps will become more intense. Often times, faults are associated with density contrasts across them—great enough to be detected with a gravity meter survey. This brings up the question of how can we recognize the possibility of faulting on a Bouguer gravity map.

Examples of gravity surveys over known faults are compared with a hypothetical fault superimposed on an assumed regional anomaly.

Aeromagnetic mapping of regional and local basement structure

Nelson C. Steenland

Regional basement structure may be mapped from aeromagnetic data by the use of the intrabasement type of anomaly and local basement structures may in turn be mapped by the use of the suprabasement type. The characteristics of these anomalies and methods used to resolve them are presented. The application of this system of regional and local mapping is demonstrated from results obtained in the North American continent and Africa.

Polar movement as indicated by rock magnetism

Lynn G. Howell and Joseph D. Martinez

The complete paper is published in Geophysics, *this issue.*

An electrical crevasse detector

John C. Cook

The complete paper appeared in Geophysics, *v. 21, p. 1055.*

Patents in the service of geophysics

O. F. Ritzmann

This paper presents a general discussion of the significance of patents and how they affect geophysical operations. Patents have become an important part of our technical literature. In spite of the exclusive character of the patent grant, the geophysical exploration art has been little handicapped by patents or patent controversies. The inventions disclosed in patents have served as stepping stones for advancing the practical application of all branches of physics to exploration techniques.

Treatment of geophysical expenditures for federal income tax purposes

J. W. Yarbro

There are no clear rules of accounting with respect to treatment of geophysical expenditures.

Whether they are to be charged off as spent or capitalized as cost of the property has important tax consequences and presents a dilemma to the tax accountant. Prior to 1942 no one questioned the right to expense all geophysical costs as incurred. Since that date the Internal Revenue Service has maintained that the answer depends upon what is done with the property after the geophysical appraisal is completed. The geophysicist who understands the accounting and tax aspects of geophysical expenditures can greatly help the tax man resolve the problem and achieve the most favorable tax result.

Geophysical history of the Chacahoula dome, LaFourche & Terrebonne Parishes, La.

W. E. HOLLINGSWORTH

The Chacahoula salt dome at LaFourche and Terrebonne Parishes, La., was first discovered by a Gulf refraction party in 1926. This was followed by later fan shooting and drilling of a test well which found caprock at 1,300 feet. Gulf then followed with more refraction work and then torsion balance work. Two more dry wells were drilled, and Gulf dropped its leases. The Sun Oil Co. took the leases and started exploration in 1934 by fan shooting. In 1938 refraction and reflection profiles were shot to explore for flank production and a discovery well was drilled. Additional reflection work was done periodically to help exploit the find and a final dome outline was completed in 1940. The northeast extension of the salt in the dome was responsible for differing interpretations of the dome outline during the exploration and drilling.

Case history of the Redwater oil field

C. J. CHAPMAN

The discovery of the Redwater oil field was purely a seismic success and was very largely responsible for the growth of the Canadian geophysical industry.

A line of one mile correlation points provided the original leads to the Redwater anomaly. Continuous profiling outlined a major isochron "thin." Although this anomaly was not fully understood, due to lack of geologic knowledge in the area, it nevertheless outlined the oil field. As a result of the discovery criteria were developed which were used in outlining an extension of the field. These criteria and their application are discussed.

Geophysical case history, Cabin Creek field, Fallon County, Montana

L. F. SCHOMBEL

Cabin Creek oil field, Fallon County, eastern Montana, is producing from a faulted subsurface anticline underlying the prominent Cedar Creek surface anticlinal trend. An upper Cretaceous structure map made from outcrop information shows little evidence of local closure. Jurassic seismic data show anticlinal folding occurring slightly southwest of the surface axis, but with less than 25 feet of critical southeast closure. Below the regional Mesozoic-Paleozoic unconformity the structure is more pronounced and more complex, the lower Paleozoic strata showing about 200 feet of critical closure. A portion of the northeast closure is caused by a pre-Jurassic normal fault downthrown to the northeast. The Cabin Creek structure was first indicated by seismic work done in 1950. The discovery well was completed in May, 1953, with a potential, after acid treating, of 1,248 barrels of oil per day on a three-quarter-inch choke from rocks of Silurian and Ordovisian age. Additional seismic work has been done subsequent to the discovery to aid in exploitation of the field.

The importance of the structural interpretation of seismic data

R. A. WEINGARTNER

At a time when complicated structural concepts appear to be the rule rather than the exception, too little effort is being spent on the study of stratigraphic and structural possibilities offered by the seismic cross section data, and too little effort is spent by the geologist in making use of the data. Steps to increase the effort envisage (1) development of qualified personnel for structural and strati-

graphic interpretation with responsibilities limited to the cross section and map making; (2) construction of seismic crossections and display of seismic map data in the most useable form for all geologists; (3) a program to encourage the use of seismic file data and the insistence by the geophysicist that the geologist make use of the data on a constant and routine basis.

Illustrations are provided to show the inadequacy of our present effort and the need for cross sections and seismic maps on a scale and in terms understandable by geological personnel of limited experience.

Difficulties in seismic prospecting resulting from bubbles in fluids

J. O. Parr, Jr.

Small percentages of gaseous bubbles present in fluids or semifluids can cause serious difficulties in seismic prospecting. Shot hole fatigue, reversals of polarity and large times for short intervals in deep well surveys, reflections coming into the side of a geophone line from surface anomalies, particularly in water, and variations in the seismic velocity through water in the Gulf of Mexico can be caused by bubbles. Both records and theoretical data are shown to substantiate this hypothesis.

The granite wash in western Canada

J. C. Sproule

This paper presents a brief summary of the granite wash oil occurrences in western Canada as they are known today. The granite wash is defined lithologically and its age relationships to overlying and underlying rocks discussed, with particular reference to the possible origin, lithology, structure, paleotopography and tectonic history of the underlying pre-Cambrian surface, on which it depends for its occurrence and development as a reservoir. The anticipated future in western Canada of this reservoir with, particular reference to the part that should be played by geophysics, is also discussed.

The SeisMAC data processing system

J. F. Bucy, H. K. Hall, and Hal J. Jones

The seisMAC is an electronic system designed specifically for processing of magnetic seismic records. High speed magnetic drum delay lines are used to provide both constant and time-variable delays between seismic traces, thus providing a means of effecting weathering, elevation, normal move out, and other time corrections. The pattern of delays introduced is controlled by a digital programmer, which permits great flexibility in operations. The system is designed to permit rapid, routine handling of magnetic records and is ideal for a central office installation. Typical system outputs are time-corrected time and depth sections.

This paper outlines briefly the theory and operation of the system and presents several examples of processed data.

A high radiometric anomaly caused by fall-out and its decay

J. O. Parr

A large and intense radio-metric anomaly, probably attributable to fall-out, is described. Five successive runs of the same traverse over a period of nearly a year show cumulative decay of the anomalous readings. Extent of the anomaly was correlated with rainfall prior to the initial readings. Deposition of radioactive material was restricted to the top surface only, and insufficient uranium or thorium was found to justify the observed radiation readings.

A theoretical study of induced electrical polarisation

Richard H. Frische

A mathematical solution was obtained and numerically evaluated for determining the depth to a saturated aquifer when prospecting for ground water by induced electrical polarization. In a hori-

zontally stratified earth model consisting of a non-polarizable overburden and of an underlying infinitely deep polarizable layer, the induced polarization potential difference for a Wenner electrode configuration is fairly independent of the resistivity contrast. The computation agrees with results from a laboratory model tank and with a field curve. This increases confidence in the validity of the results obtained from the model tank on earth models too complex for computation.

Prospecting for ground water by induced electrical polarization

VICTOR VACQUIER, P. R. KINTZINGER, and C. R. HOLMES

When a direct current between two grounded electrodes is interrupted, a potential difference between another pair of electrodes is observed by decay for about one minute or more if a substantial portion of the current path consists of fresh-water aquifier. The magnitude of this residual polarization voltage is only a few percent of the voltage that appears between the potential electrodes during passage of the current. Laboratory experiments on known clay-sand mixtures prove that the polarization effect depends on cation exchange in the clay minerals dispersed in water-saturated alluvium or sandstone. Clay content, ion content of the water, and the grain size of the matrix have to be considered in the interpretation of field data. Induced polarization increases with resistivity. Its relaxation time also increases with the grain size and therefore with the permeability of the matrix. This latter property was checked at a well field south of Alamogordo, Mexico. With 10 kw of power thick water bearing formations have been detected down to 400-foot depths. Simple characteristic field conditions have been studied in a model tank.

Cation exchange in kaolin as a factor in induced electrical polarization in aquifers

MICHEL L. LAVERGNE

Prospecting for groundwater by induced electrical polarization as first reported by V. Vacquier and P. R. Kintzinger (abstract 35th annual meeting American Geophysical Union 1954) is related to cation exchange on the clay minerals which contaminate the aquifer. A mixture of 5 percent electrodialyzed kaolinite in 100 mesh quartz sand was alternately percolated with radioactivity tagged NaCl solutions and HCl solutions. It was found that induced electrical polarization was proportional to the amount of sodium fixed on the clay which was determined radiometrically without disturbing the specimen. A small residual polarization effect was observed with HCl when the clay contained no sodium.

The use of a least squares method for the interpretation of data from seismic surveys

A. E. SCHEIDEGGER and P. L. WILLMORE

Published in GEOPHYSICS, *v. 22, p. 9. January, 1957 issue.*

Automatic methods of computing wave front and ray paths of the propagation of seismic energy with applications

W. O. HEAP

It has long been recognized that in general seismic velocities vary principally due to lithology, age, and depth of burial. This variation in velocity is usually expressed in terms of reflection time or in terms of depth. When the subsurface formations are dipping more than a few degrees it is necessary to compute the true depth and displacement of the depth points. The combination of variable velocity and dip introduce mathematical relationships which are tedious to solve by ordinary means.

This paper introduces automatic computation procedures utilizing an electronic calculator which may be programmed to solve the necessary computations involving any velocity function for the construction of 1) Wave-front charts, 2) Plotting arm scales; or 3) Tables for table-look-up operations.

Special treatment is given the linear increase of velocity with depth and the linear increase of velocity with time.

An interesting and useful application is described in detail involving 1) A variable initial velocity

with a linear increase of velocity with depth and 2) The use of two different velocity functions, the lower function representing an interval velocity in which the upper horizon varies in depth sufficiently to cause the velocity at its surface to vary over a wide range directly affecting the initial velocity of the lower function. Only one wave front chart is constructed and two supplementary charts are used for adjusting the wave front chart for use with any initial velocity.

A regional gravity survey of parts of Tooele, Juab, and Millard counties, Utah

J. Burlin Johnson, Jr., and Kenneth L. Cook

Published in Geophysics, *January, 1957 issue.*

Resistivity studies of metalliferous synthetic cores

Peter Mandel, Jr., Joseph W. Berg, Jr., and Kenneth L. Cook

Published in Geophysics, *this issue.*

NOMINEES FOR 1957–58 EXECUTIVE COMMITTEE

The following biographical sketches are presented to acquaint members of the Society with nominees appearing on the official ballot which will be mailed to all active members in good standing in June. Bylaws Article VII, Section 4, provides that "Prior to June 1, nominations in writing, signed by at least twenty honorary members or active members in good standing and accompanied by the written consent of the candidate, may be submitted to the president."

O. C. Clifford, Jr.

H. M. Thralls

O. C. Clifford, Jr., candidate for president, received a B.S. degree in 1924 and spent the following year in graduate work, at the University of Chicago. The summer of 1924 was spent in the employ of the Illinois State Geological Survey. He was employed by Humphreys Corporation in July, 1925 on one of the first torsion balance parties in the United States. Following employment in the geophysical department of the Humble Oil and Refining Company in similar work he joined the geological staff of the Houston Oil Company in West Texas. During the next five year period he held various geological and geophysical assignments with the Indian Territory Illuminating Oil Company in the Rocky Mountain and Mid-Continent areas. His initial acquaintance with the seismograph was in 1930 as client representative on the third GSI crew to take the field. Following a short period with Seismograph Service Corporation in 1933 he was employed as control geophysicist by

Continental Oil Company in 1934. In 1936 he moved to Houston as district, later regional, geophysicist for the Atlantic Refining Company. Since 1943 he has been located in Dallas as chief geophysicist for the same firm.

He has been a member of the American Association of Petroleum Geologists since 1928 and of the Society of Exploration Geophysicists since 1936. He is a member of the Dallas Geological Society; the Dallas Geophysical Society, and served as president in 1949, the year the first regional geophysical meeting was held without the cooperation of the local geological society, and district representative in 1950, 1951, 1952. He has served on the committees for both *Geophysical Case History* volumes. Published articles have appeared in the *Bulletin* of the AAPG and in *Geophysical Case Histories*.

H. M. THRALLS, candidate for president, received a B.S. degree in 1932 and an M.S. degree in 1934 from the University of Oklahoma. He joined Shell Oil Company as a seismic computer in August 1934. In 1936 he became a party chief for Seismograph Service Corporation. He was promoted to supervisor by that firm in 1939, to chief geophysicist in 1945, and to vice president in 1949. He resigned from Seismograph Service Corporation effective February 1, 1955 to organize the geophysical contracting firm of Geo Prospectors, Inc. and the geophysical consulting firm of Thralls, Green & Perry. Both firms are headquartered in Tulsa, Oklahoma.

Mr. Thralls is a member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists, the American Geophysical Union, the Tulsa Geological Society, the Geophysical Society of Tulsa, and the Oklahoma City Geological Society. He has served the Geophysical Society of Tulsa on numerous committees, as district representative to the National Council, as vice-president in 1947, and as president in 1950. His services to the Society of Exploration Geophysicists include a term as secretary-treasurer, chairman of the membership committee, chairman of the business office committee, chairman of the safety committee, and as a member of various other committees.

OTIS B. HOCKER

BEN F. RUMMERFIELD

OTIS B. HOCKER, candidate for vice-president, received the B.S. degree in electrical engineering from Texas A. & M. College in 1932 and returned there in 1935 to do graduate work. In April 1935 he was employed as computer by The Texas Company on a seismic party in the Gulf Coast area. He was transferred to Illinois in 1936 and promoted to party chief in 1937. In March 1938 he accompanied a gravity party to Egypt as physicist-in-charge and while in that country was made party chief of a seismic party in 1939. Immediately upon return to the United States in 1940 he entered the armed forces and served throughout World War II, being released with the rank of lieutenant colonel in 1946, at which time he returned to Texaco.

After a series of assignments as party chief, he was promoted to supervisor of field operations and located in Houston, Texas in February 1948. In September 1949, he was assigned to the position of geophysicist on the producing department general manager's staff, and in July 1950 promoted to assistant manager of the geophysical division and to manager of that division in April 1954, the position he now holds.

He is a member of the Society of Exploration Geophysicists and is currently 1st vice president of the Houston Section which he has served as District Representative since 1954.

BEN F. RUMMERFIELD, candidate for vice president, was graduated from the Colorado School of Mines in 1940 with a degree of Engineer of Geology, having majored in geophysics. He was employed by Seismograph Service Corporation as a rodman and advanced to party chief, working in a major portion of the geological provinces of the United States. In 1945 he went to Venezuela in the capacity of seismic supervisor. He returned to the United States in 1947 and completed the advanced management program at Harvard Graduate Business School. He was then transferred to Mexico, where he worked as an assistant manager for three years. During this period he was instrumental in setting up and operating the first offshore work done in Mexico in the Bay of Campeche. He joined Century Geophysical Corporation in 1950 as manager of seismic operations in the United States and Canada, and was appointed executive vice president in 1955, which position he now holds.

Ben is chairman of the SEG special committee on radioactive mineral exploration and is a member of the public relations committee. He has served as chairman of the SEG standing committee on publicity and as a member of technical program committees. He is a past vice president of the Geophysical Society of Tulsa.

Rummerfield received the Society's Best Paper Award in 1954 for his paper "Reflection quality," a fourth dimension" and has written other papers appearing in GEOPHYSICS and other publications.

He is a member of the SEG, AAPG, Canadian SEG, Asociacion Mexicana de Geologos Petroleros, Geophysical Society of Tulsa, Tulsa Geological Society, American Geophysical Union, Sigma Gamma Epsilon, and Blue Key.

HOWARD E. ITTEN

CURTIS P. HARKINS

HOWARD E. ITTEN, candidate for secretary-treasurer, was graduated from The Colorado School of Mines in 1941 with a Geological Engineer degree, majoring in geophysics. Upon graduation he accepted employment with the Stanolind Oil and Gas Company on a seismograph field party in western Kansas. He remained with this firm for eleven years, variously filling the positions of computer, assistant party chief, party chief, assistant division geophysical supervisor, and division geophysical supervisor. In January of 1947 he moved to Fort Worth, Texas with Stanolind and in the fall of the

same year became head of Stanolind's geophysical department in their North Texas-New Mexico division. He has maintained his residence in Fort Worth since that time.

In March of 1952 he resigned from Stanolind to form Empire Geophysical, Inc., the firm with which he is now associated as president. In 1953 he organized, as a subsidiary of Empire Geophysical, Inc., the Empire Velocity Service Company of which he is also president.

Mr. Itten has been a member of the Society of Exploration Geophysicists for the past sixteen years. He is a member of the American Association of Petroleum Geologists, the American Geophysical Union, and the Seismological Society of America. He is past president of the Fort Worth Geophysical Society, and during the past year has been general chairman for the tenth annual midwestern regional meeting. He was elected to the post of district representative from Fort Worth for two years, 1956–58. He is a member of the Fort Worth Geological Society, the Geophysical Society of Oklahoma City and the Permian Basin Geophysical Society. He assisted in the organization and was one of the sponsors of the Trans-Pecos student section at Texas Western College.

CURTIS P. HARKINS studied electrical engineering at Louisiana State University, 1931–36. In February, 1936, he was employed as an observer trainee with Independent Exploration Company on one of its seismograph crews. He served in various technical field jobs, including seismic observer and computer, and gravity operator, computer and party chief. In 1942 he returned to I.X.'s seismic operations as party chief. He became a seismic supervisor in 1949 and was appointed to vice-president in charge of personnel and operations in 1952. His present position is vice-president and assistant general manager for Independent Exploration Company. He has been a member of the Society of Exploration Geophysicists since 1936. He is now serving as 2nd vice-president of the Houston Section, Society of Exploration Geophysicists and is a member of the Houston Geological Society.

LAWRENCE Y. FAUST

EDGAR J. STULKEN

LAWRENCE Y. FAUST, candidate for editor, received the Bachelor of Science degree in physics in 1925 from Franklin and Marshall College. He received the degree of Ph.D. in physics from the University of Pennsylvania in 1930. In 1926 he began work in geophysics for the Sun Oil Company and was engaged primarily in making magnetic surveys. He joined Geophysical Research Corporation in 1930, serving as seismograph party chief. Upon transfer to Amerada Petroleum Corporation, he served as geophysical supervisor. His work has been primarily with seismograph reflection and refraction methods but has also included the supervision of gravity and electric surveys and interpretations. At the present time he supervises a group investigating special geophysical problems.

Since 1953 he has been responsible to the Conorada and Sinclair Somal group of companies for their geophysical explorations in East Africa.

Dr. Faust served as an associate editor of GEOPHYSICS for the term 1953–1955.

As prior past president of The Geophysical Society of Tulsa, he serves on the executive committee of that society and as a district representative to the Society of Exploration Geophysicists.

Papers by Dr. Faust which have appeared in GEOPHYSICS include "Seismic velocity as a function of depth and geologic time" for which he received the Society's best paper award for 1951.

EDGAR J. STULKEN, candidate for editor, graduated from Blinn Junior College in Brenham, Texas, in 1931, winning membership in Phi Theta Kappa, a national honorary scholastic society. After teaching in a country school, he studied at the University of Texas, receiving there the B.A. degree with honors in physics in 1934 and the M.A. degree in mathematics in 1935. While a student he taught mathematics at the Texas Wesleyan College which was then in Austin and served as a student assistant at the university.

In 1935 Mr. Stulken joined Geophysical Service Inc. as a field crew helper and has since been affiliated with this company continuously except for about two years. From 1940 to 1942 he taught mathematics and physics at Allen Military Academy in Bryan, Texas. In G.S.I. he has held various positions and is at present chief seismologist. He supervises an extensive company correspondence training program and has prepared a number of technical reports. Several of his papers have been published in GEOPHYSICS.

He has belonged to Phi Delta Kappa, a national honorary education fraternity, and the Mathematical Association of America. At present he is an associate member in the American Association of Petroleum Geologists and is an active member in the Society of Exploration Geophysicists, the European Association of Exploration Geophysicists, the Dallas Geophysical Society, the Dallas Geological Society, and the Geological Society of America.

FELLOWSHIPS 1957–58
SAINT LOUIS UNIVERSITY

The Department of Geophysics and Geophysical Engineering of Saint Louis University announces that applications are now being accepted for two fellowships supporting graduate study in geophysics.

The fellowship sponsored by the Gulf Research and Development Company is available for a student in geophysics who has completed at least one year of graduate study and is qualified to work for the doctorate. The stipend is $2,000 per year, paid in nine monthly installments. In addition the fellowship provides for payment of tuition and fees.

A fellowship available to either a promising first year graduate student, or one with more advanced work, is provided by a grant from the Shell Oil Company. The research being conducted under this grant, and in which the fellow is expected to participate, is on the fundamental nature and behavior of explosion generated elastic waves. The stipend is $1,800 per year, on a twelve month basis.

For further information and for application blanks, write to: Dean of the Graduate School, Saint Louis University, 221 North Grand Boulevard, Saint Louis 3, Missouri.

Applications should be filed before May 15, 1957.

ANNOUNCEMENTS

SEG SCHOLARSHIP PROGRAM REACHES $8,000 ANNUALLY

Bart W. Sorge, chairman of the public relations committee, and Richard Brewer, chairman of the student membership committee, have announced that six companies will sponsor scholarships this year totalling over $8,000 which will be administered by the SEG student membership committee. Several companies have discontinued the practice of sending Christmas gifts to their clients who now receive instead Christmas cards announcing the scholarship grants in geophysics. Mr. Sorge advises that six more companies have indicated interest in the program.

The following scholarships are currently being administered by the student membership committee of the Society of Exploration Geophysicists.

Mayhew Supply Company, Inc.

This scholarship is for $3,000.00. It provides $750.00 per year for four years toward the cost of tuition, laboratory fees, etc. It must be in a college or university that offers a bachelor's degree in geophysics. The scholarship must be awarded to a son or daughter of a person who is totally engaged in the geophysical industry—either a geophysical company, a geophysical branch of an oil company, or a contract drilling company. The student must concentrate in geophysics for at least four years of college work following a plan that will lead to a bachelor's degree.

Griffin Tank and Welding Service

This scholarship provides $750.00 per year toward the cost of tuition, laboratory fees, etc., and must be re-awarded each year. At the discretion of the committee, however, the same undergraduate may receive the scholarship for four consecutive years. It is not necessary for either of the parents of the recipient to be engaged in the oil and gas industry, but the student must pursue a course directed toward a career in geology or geophysics.

The Cordie Hawthorne Scholarship

This scholarship has been established as a memorial by Herb J. Hawthorne, Inc. It provides $750.00 per year toward tuition, laboratory fees, etc., and will be awarded on an annual basis. It may be awarded to the same undergraduate student for four consecutive years, but a student receiving it for the first time need not be a freshman. He (or she) must, however, pursue a course directed toward a career in geophysics.

Southwestern Industrial Electronics Co., Inc.

This scholarship provides $750.00 per year toward the cost of tuition, laboratory fees, etc. It will be awarded on an annual basis, but the same undergraduate student may receive it for four consecutive years. The recipient need not be a freshman, but he (or she) must carry as much geophysics as possible. In awarding this scholarship, preference will be given to those persons who are interested in entering the instrumentation field of geophysics after graduation.

Grant Body and Equipment Company

The Grant scholarship provides $750.00 per year toward tuition and fees and is to be awarded on an annual basis. It may be awarded to the same undergraduate student for four consecutive years, but a student receiving it for the first time need not be a freshman. The recipient must, however, pursue a college course directed toward a career in geophysics.

Geophysical Service Incorporated

This grant will provide $1,500.00 per year for two scholarships to be awarded on an annual basis, but the requirements for qualification are not yet available.

Vector Manufacturing Company

This scholarship will provide $750.00 per year and will be awarded annually, but the requirements for qualification are not yet available.

EXPLORATION CONSULTANTS, INC., Tulsa, Oklahoma, has granted $100.00 to start a group-sponsored scholarship, which will be granted when the fund reaches a sufficient amount.

APPLICATION FORMS may be obtained by writing to

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536
Tulsa 1, Oklahoma

UTAH GEOPHYSICAL SOCIETY CHARTERED

At a regular meeting of the Utah Geophysical Society held at the Newhouse Hotel in Salt Lake City on Friday, October 5, 1956, a new constitution was adopted unanimously by the 22 SEG members present, enabling the society to become a local section of the Society of Exploration Geophysicists. A petition was then signed and forwarded to the executive committee of SEG who submitted the petition to the council at its meeting October 30, 1956 in New Orleans. The council unanimously approved the charter of the Utah Geophysical Society as the Utah Section of SEG.

Officers of the new section are T. E. Hobbs, president; J. R. Cheney, 1st vice-president; Kenneth L. Cook, 2nd vice-president; and J. W. Erwin, secretary-treasurer.

COMMITTEE ON RADIOACTIVE MINERAL EXPLORATION

The advisory committee on radioactive mineral exploration was formed under the auspices of the AAPG and was ably directed by Dr. Fred Lahee. Its primary functions were to advise concerning and stimulate radioactive mineral exploration, particularly in areas where petroleum exploration is in progress.

Last spring it was decided that this committee had served its purpose and it was therefore disbanded. The final report of the committee appears on page 1442 in the *Bulletin of AAPG* for June, 1956. At that time the following thinking concerning the continuance of the committee was suggested:

1. The American petroleum and mineral industries have developed mineral exploration personnel, instruments, techniques and philosophies to the highest degree the world has known. The radioactive mineral investigations of the free world need this exploration maturity, experience and ability successfully to combat those economies which are in opposition to ours.
2. To have such a committee with a successful history might prove invaluable in the event of a national emergency. These responsibilities on the part of the petroleum and mining industries are much more acceptable and effective when extended on a volunteered basis rather than on a requested or demanded basis.
3. The basic energy industries within the next thirty years will find themselves either directly in the business of at least partially producing energy from atomic sources or directly in competition with other industries or *agencies* similarly engaged. In our effort to continue to develop our free enterprise system and to further the industries' public relations we should maintain a positive and aggressive attitude in this matter. By closely associating with the problems and potentialities of radioactive minerals the petroleum and mining industries are better equipped to combat the intervention of either other industries or political groups in a field so closely allied with theirs.
4. A much better understanding is desirable among the general petroleum industries and those industries presently engaged in producing and using radioactive minerals. This committee will help to accomplish this purpose.

It was also suggested that "the exploration for nuclear materials will become a matter of real concern to the geophysicist before any large number of geologists are engaged in research, therefore, it is more likely that such a committee would succeed if set up under the SEG."

The members of the committee, it was suggested, should be individuals who are particularly active in exploration work in the different fields of petroleum geology, uranium geology and/or geophysics. By including engineers from petroleum, mining, and the academic fields it would prove effective in securing cooperation in the exploration for atomic energy minerals.

It should be the purpose of this group: (1) to determine if such a committee should formally exist; (2) If such a committee is desirable, to establish its objectives. Members of the committee are: F. H. Lahee, Lewis MacNaughton, Ing. Antonio Garcia Rojas, John Hollister, Al Hintze, Paul Lyons, John Masters, Stan Rose, Marvin Kay, Ralph Holmer, and Ben F. Rummerfield, chairman.

NEW OFFICERS OF THE PERMIAN BASIN GEOPHYSICAL SOCIETY

Left to Right: John E. Clark, *secretary*, Union Oil Company of California; B. Frank Owings, *first vice-president*, Forrest Oil Corporation; R. Maxey Pinson, *president*, Union Oil Company of California; E. E. Fickinger, *second vice-president*, Continental Oil Co., and B. Arnold Heidt, *treasurer*, Dawson Geophysical Company.

EAEG FORMS GEOPHYSICAL ACTIVITIES COMMITTEE

The European Association of Exploration Geophysicists will form a committee to report on geophysical activity in Europe in cooperation with the SEG committee on geophysical activity, it has been reported by Homer G. Patrick, chairman of the SEG committee. Upon organization of the EAEG committee details of a plan for incorporation of its surveys with the world-wide report of the SEG committee will be worked out. The joint venture of the two societies is expected to take effect next year, Mr. Patrick said.

TEXAS A & M STUDENTS ORGANIZE

The A & M College of Texas Student Geophysical Society was organized in November, 1956 with 17 members. Sponsored by Dr. Paul Weaver, honorary member of SEG, the society was organ, ized largely through the efforts of L. T. Gregg and Steve R. Rokke, both student members of SEG- with encouragement and help from Dr. Peter Dehlinger. Mr. Gregg is president of the new society, and Mr. Rokke is vice-president. Robert T. Smith, who with eleven other A & M students joined SEG recently, is secretary-treasurer. Only student members of SEG may belong to the new student society.

By executive order No. 639-B, on January 24, 1957 the Society of Exploration Geophysicists became affiliated with the A & M society, which is now referred to as the A & M College of Texas Section of the SEG. Meetings are held on the second Tuesday of each month at 7:30 P.M. in the geology building on the campus. Officers of the society may be addressed in care of the geology and geophysics department, Texas A & M College, College Station, Texas.

CANADIAN SEG SUPPORTS CALGARY TECHNICAL LIBRARY

Organized just over one year ago, the Calgary Technical Library is already rapidly running out of space. Librarian Kay Taylor reports that as additions to the library are received, they must be stacked on the floor of the Calgary City Library.

Chairman of the technical library, our vice-president, Cam Sproule, reports that the following donations have been received:

Association of Professional Engineers of Alberta	$500.00
Canadian Institute of Mining and Metallurgy	600.00
Canadian Society of Exploration Geophysicists	633.00
Oilfield Technical Society	300.00

Additional donations amounting to $1,700.00 have been promised and a revenue of almost $950.00 has been realized from sales of duplicates and other miscellaneous sources.

Although only $1,500.00 has been expended for books, purchases planned for the near future will make use of funds now on hand.

Part of the present library has been made up by donations of technical literature by various firms and individuals. The committee would welcome further technical literature of all descriptions.

Chairman Sproule suggests that the technical library committee would very much like to have suggestions and requests from users and potential users.

The idea of a local technical library is a sound one. Proof lies in the success of the Calgary library which now faces serious expansion problems after just over one year's operation.—*The Alberta Professional Engineer*

SECOND CUBAN PETROLEUM CONGRESS

The Second Cuban Petroleum Congress will be held in Havana May 5–11, 1957. It will include an industrial exhibit open to the public and technical and scientific sessions open to registrants exclusively.

Work sections shall be six: Section I—Geology, geophysics and geochemistry; Section II—Drilling and production; Section III—Processing, distribution and utilization; Section IV—Research, development and testing; Section V—Education and training of personnel; Section VI—Management, economics and law.

Papers may be in Spanish, English or the native tongue of the author's country of residence. Spanish and English shall be official languages. Manuscripts should be on hand by March 1, 1957. Title of paper, author's name and a résumé of the subject matter should be submitted as early as possible to permit preparing a preliminary program for circulation.

Additional details may be obtained addressing II Cuban Petroleum Congress, Edificio Habana 800, Havana, Cuba.

MOODY TO HEAD AAPG

GRAHAM B. MOODY, consulting geologist of Berkeley, California and a member of SEG will become the 41st president of the American Association of Petroleum Geologists on April 4, 1957 according to President Theo. A. Link of the Association. Other members serving with Moody on the 1957–1958 executive committee will be

Past. pres.—Theo. A. Link, Cree Oil of Canada, Ltd.

V-pres.—Byron W. Beebe, Keating Drilling Company, Oklahoma City, Oklahoma

Secty.-treas.—William J. Hilseweck, Blackwood & Nichols, Dallas, Texas

Editor—Sherman A. Wengerd, University of New Mexico, Albuquerque.

The new AAPG officers will assume their responsibilities of directing this 13,500 member organization at the close of the 42nd annual meeting of the Association to be held in St. Louis, Missouri, April 1–4 at the Kiel Auditorium.

Retiring members of the present AAPG executive committee are:

Past pres.—G. M. Knebel, Standard Oil Company (N. J.), New York City

V-Pres.—Ben H. Parker, Frontier Refining Company, Denver Colorado
Secty.-treas.—W. A. Waldschmidt, consulting geologist, Midland, Texas
Editor—W. C. Krumbein, Northwestern University, Evanston, Illinois.

SSC OCCUPIES NEW PLANT

Seismograph Service Corp., world-wide seismic firm announces the opening of its new $900,000 Tulsa headquarters at 6200 E. 41st St., Tulsa Oklahoma. Located in the area of one of the fastest growing, recently developed industrial districts, the new location will be adjacent to the Skelly Drive By-pass scheduled for completion soon. GERALD H. WESTBY, president of this pioneer geophysical research organization, said several weeks will be required to complete all details of exterior planting and parking areas.

Personnel and equipment from seven separate Tulsa locations are now at one central point and the move will mark the first time the entire Tulsa organization has been under "one roof" since its organization. Climaxing the celebration of the firm's 25th year, occupation of the new seismic center affords the company some 70,000 square feet of research and manufacturing space. The main building, a two-story structure, houses SSC's general offices, seismograph, LORAC and other electronic laboratories. Westby, who has been president of SSC since 1935, said the move will greatly increase the company's efficiency by bringing all the operations into one location.

The company's first location, when organized in 1931, was in the Guaranty Laundry building, Tulsa. Two years after its organization SSC moved into the Kennedy Building, where it has been up to the present time. "Three years after we organized we had crews in Poland and Rumania," Westby recalled. "That is when we first considered ourselves to be truly international." Subsequent growth of the company, with operations on every continent and in nearly every oil producing country in the world, forced the firm to spread out into seven other Tulsa locations.

The company is now operating in 22 countries on five continents, and has subsidiaries in England, France, Italy, Libya, Colombia, Brazil, Bolivia, Mexico, Venezuela and Canada.

The British subsidiary, Seismograph Service, Ltd., has headquarters on a famous estate at

Holwood, England. Located 15 miles southeast of London, the 105-room manor house is the former home of one of England's famous prime ministers, William Pitt the Younger.

EARTH SCIENCES LABORATORY AT MIT

The Massachusetts Institute of Technology has established a laboratory of earth sciences, Dr. George R. Harrison, dean of science at MIT, has announced.

The laboratory, which will be under the direction of Professor Henry G. Houghton, head of MIT's department of meteorology, will attempt a new and integrated approach to experimental and theoretical investigations of man's environment: the atmosphere, the oceans, and the intervening land masses, including the interior of the solid earth.

Dr. Houghton, who will head the new laboratory, has been in charge of meteorology at MIT since 1945 and a member of the staff there since 1928. He is well known for his research in cloud physics and atmospheric radiation, and for some of his earlier studies with specific applications to aeronautics.

PLANNERS OF THE TWENTY-SEVENTH ANNUAL MEETING

Plans are under way for the 27th Annual Meeting of SEG at the Statler-Hilton Hotel, Dallas, Texas, November 11–14. Three meetings have already been held by the convention committee chairmen: (left to right) O. C. Clifford, Jr., housing; E. O. Vetter, finance and vice-chairman; C. J. Deegan, publicity; J. P. Woods, vice-president of the Society; Mrs. Ray Stehr, ladies' program; Glenn M. Conklin, technical program; John A. Cathey, exhibits; F. J. Agnich, general chairman; and Colin Campbell, business manager of the Society. **Papers for the meeting must be submitted to Mr. Conklin by July 1, 1957.**

THE MARINE SONOPROBE

A unique tool for exploring the ocean floor and sediments 80 feet or more beneath it—useful for offshore oil exploration, submarine pipe line constructions, underwater salvage operations, and other purposes—has been developed by research scientists of Magnolia Petroleum Company, southwestern affiliate of Socony Mobil Oil Company, Inc.

The instrument, called the Marine Sonoprobe, will be made available to the oil industry and other users under arrangements recently completed by Socony Mobil and Magnolia Petroleum Company, with Fairchild Aerial Surveys, Inc., which will offer Marine Sonoprobe surveys on a worldwide basis as a commercial service.

The Marine Sonoprobe is similar in construction and operation to conventional recording echo sounders used for measuring the depth of water but has been specially designed to get echoes from beneath the ocean floor.

The instrument uses a special sound source which produces sound pulses of much lower fre-

quency and much greater power than in conventional echo sounders. These pulses penetrate bottom sediments and are reflected back from layers beneath the bottom.

The sea floor and layers beneath it are displayed on a small television picture tube and are also recorded as a continuous profile on electrosensitive paper.

The Marine Sonoprobe is intended for use in water-covered areas of the world where conditions are favorable. It can be mounted on shallow-draft boats for use in shallow water or on larger vessels for use in deeper water.

The instrument was originally designed, built, and tested for underwater geophysical research at Magnolia's Field Research Laboratory, Dallas, Texas. Magnolia and General Petroleum Corporation, Socony Mobil's west coast affiliate, have used it as a reconnaissance tool in offshore oil exploration. Magnolia has also used it for mapping the routes of underwater pipe lines and in surveying sites for offshore drilling platforms, for which pilings must be driven into the sea bottom.

In addition, the new tool has been used to find buried beds of oyster shells, which are then dredged from beneath the ocean floor for use in road construction and in making cement, chemicals, and fertilizer.

Experience with the Marine Sonoprobe indicates that it will provide reliable maps of shallow salt domes, shallow faults, buried ancient channels and valleys, and shallow geological structures. It may also give useful information to determine the extent of silting in reservoirs.

Fairchild Aerial Surveys, Inc., with headquarters in Los Angeles, California, is a pioneer firm in aerial mapping and airborne geophysical surveys. A wholly-owned subsidiary of Fairchild Camera and Instrument Corporation, it has operated in 36 countries outside the United States. Its Marine Sonoprobe oprations will be directed by F. W. Hinrichs, captain, U.S.N.R., the Company's chief geologist.

SAN DIEGO STATE COLLEGE STARTS GEOPHYSICS PROGRAM

San Diego State College, San Diego 15, California, has established a new program in geophysics, according to Baylor Brooks, chairman of the department of geology. Dr. Brooks said two of the geology department's six staff members are well acquainted with the geophysics field through personal experience in both mining and petroleum. The new program needs the assistance of industry in obtaining instruments and equipment for demonstration of principles and applications, Dr. Brooks said.

McGILL UNIVERSITY OFFERS MINERAL EXPLORATION DEGREE

The Department of Geological Sciences is offering a new two-year sequence of courses leading to a degree of Master of Science (applied) in mineral exploration, it has been announced by T. H. CLARK, Chairman. The new degree is designed to provide advanced professional training. "New discoveries and techniques in geology, mining, metallurgy, physics and chemistry have made this new sequence desirable in order to provide adequate training for students entering the mineral exploration field," Clark said. The various departments concerned with these subjects are co-operating in teaching the new courses. The legal and financial aspects of mineral exploration are also touched upon.

"With a constantly rising demand for metals and minerals, it is apparent that mineral exploration is becoming increasingly important," said Dr. Clark. The new technical methods of exploration that have already been developed require more basic training than can be given in undergraduate work.

The new mineral exploration course at McGill University may be approached either from the bachelor's degree in mining engineering or from the B.Sc. degree with honors in geology. Students who complete the M.Sc. (applied) sequence with high standing may continue towards the normal Ph.D. (geology) degree.

TECHNICAL PERSONNEL RECRUITING EXPOSITION

Aimed at correction of the technical manpower shortage, a Technical Personnel Recruiting Exposition has been scheduled in Chicago for five days, June 8 to 12.

Presented in conjunction with the National Technical Career Conference, this exposition will be held in the Sherman Hotel, featuring exhibits by leading research and manufacturing organizations, to present maximum information to the personnel attending.

Here is a never-equalled opportunity for those with degrees in sciences and engineering to choose a new professional responsibility, making maximum use of their abilities.

The exhibitors will offer a wide selection of professional opportunities. More information will be available at this exposition about the job and the company behind it than has ever been given to prospective technical employees.

There will be no charge to the registrants, but those wishing to attend must register in advance. Registration forms and the bulletin "How to prepare an effective work experience résumé" can be secured by writing the director, Marcus W. Hinson, Technical Career Conference, 19 South LaSalle Street, Chicago 3, Illinois.

PETROLEUM ENGINEERS ORGANIZATION RE-NAMED

The Society of Petroleum Engineers of AIME has emerged as the new name of the established organization for professional engineers in the oil industry. By action of the board of directors of the American Institute of Mining, Metallurgical and Petroleum Engineers, at the annual meeting of the Institute in New Orleans, the three branches have been renamed to denote the professional status of the membership in the industries they represent.

In addition to the Society of Petroleum Engineers, the new titles of the former branches of the 87-year-old Institute are Society of Mining Engineers of AIME, and Metallurgical Society of AIME.

To the oil industry, the development gave new emphasis to the rapidly growing importance of engineering.

"This action signalizes a maturity which the petroleum engineering field has fully achieved," said John P. Hammond, Amerada Petroleum Corporation, Tulsa, new president of the Society.

Operation of the three societies under the new by-laws became effective February 26, 1957.

PERSONAL ITEMS

Members of the Society are invited to notify the business manager of any changes in their positions or companies for announcement in this section. Members are further invited to check with the public relations departments of their companies to assure that the Society is on their mailing lists to receive publicity releases.

BART W. SORGE, former secretary-treasurer of the Society and currently chairman of the public relations committee, received the *Award of Merit* from the San Gabriel district, Boy Scouts of America, in December, and the *Silver Beaver Award* from the San Gabriel Valley Council in January for distinguished service to boyhood. This was the result of seven years of volunteer effort with the Boy Scouts of America. Bart is currently adult advisor to an explorer group, as well as Jamboree Scoutmaster of a Jamboree Troop late this summer. He will then take over as chairman of the sustaining membership drive for the whole council, an effort which will require raising about $80,000, and he will probably serve on the council's board of directors.

COLIN CAMPBELL, business manager of the Society, was elected a director by the Council of Engineering Society Secretaries at its meeting in New York last January. L. Austin Wright, general secretary of the Engineering Institute of Canada, Ottawa, was elected president; Allan Ray Putnam, assistant executive secretary of the American Society of Tool Engineers, Detroit, vice-president; N. S. Hibschman, secretary of the American Institute of Electrical Engineers, New York, secretary; William P. Youngclaus, executive secretary of the American Society for Quality Control, Milwaukee, treasurer; Charles S. Doerr, executive secretary of the Engineers' Club of Philadelphia, director; and William H. Evans, executive secretary of the Engineers' Society of Milwaukee, director.

ALBERT TAYLOR, Amerada Petroleum Corp., Box 2040, Tulsa 2, Oklahoma, has a complete collection of GEOPHYSICS which he would be willing to sell.

GEORGE L. PARKHURST, vice-president of Standard Oil Company of California, received the Honor Scroll of the Western Chapter of the American Institute of Chemists, May 29, 1956, in Los Angeles.

HENRY SALVATORI, president of Western Geophysical Co., has been named chairman of the United Republican Finance Committee of Los Angeles County.

DR. YASUO SATO, assistant professor at Tokyo University and faculty member of the Earthquake Research Institute, is spending the winter term in research with PROFESSOR FRANK PRESS at the Seismological Laboratory of the California Institute of Technology as an Alfred P. Sloan Foundation Fellow.

LYNN D. ERVIN, president of the Ervin Geophysical Corp., and Oklahoma City member of the SEG publicity committee, spoke on exploration geophysics as a vocation before the Oklahoma City University Geology Club November 29, 1956. He distributed copies of "Careers in Exploration Geophysics" to the students present.

CONSTRUCTION has begun on a 10,000 square-foot, single-story administration building for Magnolia Petroleum Company's geophysical laboratory located on Harry Hines Boulevard in Dallas.

The new structure, scheduled for completion in March 1957, includes a library, conference room, classroom, drafting room, auditorium, dark room and 14 laboratory and administrative offices.

According to PAUL E. NASH, director of Magnolia's geophysical exploration, occupation of these new facilities will relieve crowded conditions in the present building and provide space for the creation of an acoustical well-logging service department. It will also make space available for additional electronic data reduction equipment which will enable more accurate and faster analysis of magnetic seismic recordings.

GERALD H. WESTBY, president of Seismograph Service Corp., Tulsa, recently announced the promotion and transfer of two employes to the firm's Canadian subsidiary headquarters in Calgary, Alberta, Canada. LAUREN G. MORRIS, Billings, Montana, and GLENN E. BLACKLEDGE, Mexico City, Mexico, were promoted concurrently with a statement of change in the organization of the Canadian affiliate following resignation of H. C. BICKEL, vice president of Seismograph Service Corp., of Canada.

RUSSELL W. ANDERSON has been named manager of the newly-formed industrial engineering department of Geophysical Service Inc.

EDWARD A. KRIEG, JR., formerly chief geophysicist for Southern Production Company in Fort Worth, has opened his consulting office in New Orleans. Mr. Krieg was with Sidney Schafer & Co., in Houston prior to joining Southern Production in 1952. His background of experience extends from Canada to Venezuela, and includes some Middle East work as well as pre-war seismic exploration in the East Indies.

EDWARD B. WASSON, Cosden Petroleum Corporation's former division geologist in Denver, has been promoted to manager of the Rocky Mountain Division, according to Marvin M. Miller, vice president in charge of the producing division. Wasson replaces J. S. Cosden, Jr., who resigned from the company recently.

JACK L. HOLLIS, chief geophysicist for British-American Oil Producing Co., has been appointed to the newly created position of exploration coordinator. The promotion became effective January 1, 1957, according to the announcement by Mr. J. E. Matter, vice president of exploration. SHERMAN L. VENCIL was made area geophysicist of the Company's southern and southwestern divisions comprising Texas, Louisiana, Mississippi, and southern New Mexico. WALTER SPECKHARD, geophysicist for the Company's central division was transferred from Oklahoma City to the Dallas head office and promoted to area geophysicist. This will include Kansas, Nebraska, Oklahoma, and the Rocky Mountain States.

PROFESSOR S. K. RUNCORN, head of the department of physics at the University of Durham, King's College, Newcastle upon Tyne, England, was appointed visiting professor of physics at the University of Texas, Austin for the month of December 1956. Dr. Runcorn, who is a fellow of the Roval Astronomical Society, gave a series of talks on the earth's magnetism.

GEOPHYSICAL SERVICE, INC., of Dallas, Texas, has given the University of Kansas department of geology a complete set of exploration seismic equipment for use in the geophysical teaching program.

Dr. William W. Hambleton, associate professor of geology, said that with this gift K.U. now has representative items of almost every kind of equipment used in geophysical exploration for possible deposits of oil and of other minerals, and in ground water studies.

A. D. DUNLAP, associated for 23 years with Independent Exploration Company, was recently made director of operations for IX. Before his promotion he was the manager of Independent Exploration's Canadian branch.

EDGAR A. FAIN has just been named vice president and general manager of Eastman International Company, whose main offices are in Denver, Colorado.

STANOLIND OIL AND GAS COMPANY took the name of *Pan American Petroleum Corporation* on February 1, 1957. E. F. Bullard, president, said the change was made for two reasons: to eliminate any possibility of confusion in the public mind between Stanolind Oil and Gas Company and other oil companies with names similar to or having a significance similar to the Stanolind name, and to give the Tulsa-based firm a name more indicative of the geographical extent of its operations.

J. C. BELSHÉ was appointed lecturer and researcher in geomagnetism at the University of Cambridge January 1, 1956. He is continuing his association with the geophysics branch of the U. S. Geological Survey on a "W.A.E." status.

DR. BENO GUTENBERG, Director of the Seismological Laboratory of the California Institute of Technology, has been awarded the Emil Wiechert Medal of the German Geophysical Association in appreciation of his accomplishments in seismology and in the investigation of the earth's structure.

This is the second award of the medal, founded in 1955, for outstanding accomplishment in geophysics.

THE APPOINTMENT OF RODOLFO MARTIN to manager of the Mexico Division of Geophysical Service Inc. has been announced by GSI President F. J. AGNICH.

Martin will maintain headquarters in Mexico City and will report to J. W. THOMAS, president of GSI's Latin American operating company.

JOHN E. PALMER has been appointed sales engineer for Seismograph Service Corporation to handle selling of the firm's geophysical equipment it was announced recently. GERALD H. WESTBY, president of the firm, made the announcement following the decision of the company's board of directors to place SSC geophysical equipment on the open market.

The partnership of RUPNIK AND BALLOU has recently moved to new offices on the 11th floor, Hunt Building, Tulsa. The firm is comprised of JOHN J. RUPNIK, ALBERT L. BALLOU, JR., ALVIN J. SCHISLER and HERMAN J. SCHMALZ.

FLYING OF A SHORAN-GUIDED AIRBORNE MAGNETOMETER SURVEY for oil began last February. The survey was to cover 40,000 square kilometers of uncharted jungle in northern GUATEMALA.

Aero Service Corporation of Philadelphia is performing the survey for 15 oil companies. Field operations will require four months, and the compilation of Shoran and magnetometer data will be completed next October. Cost of the work will be about a half million dollars.

A NEW SCIENTIFIC ADVISORY BOARD has been established by Hycon Aerial Surveys, Inc., Pasadena, Calif. The four-member board will advise the firm on continuing developments in aerial surveying, announced Grover Judy, executive vice president and general manager. Original members of the board are Charles L. Miller, Massachusetts Institute of Technology; Francis H. Moffit, University of California; Robert S. Brandt, chief of the photogrammetric division and KENNETH E. HUNTER, chief of the geophysics division.

CALENDAR OF MEETINGS

1957

April

1– 4 American Association of Petroleum Geologists 42nd Annual Meeting—and Society of Economic Paleontologists and Mineralogists 31st Annual Meeting, Kiel Auditorium and Jefferson Hotel, St. Louis, Missouri (E. W. Ellsworth, Box 979, Tulsa, Oklahoma)

25–27 American Physical Society, Washington, D. C. (K. K. Darrow, Columbia University, New York 27, N. Y.)

29–May 1 American Geophysical Union 38th Annual Meeting, Washington, D. C. (vide Trans. A.G.U., v. 37, Oct., 1956, p. 663.)

May

15 Pacific Coast Section SEG, Spring Meeting, Tejon Hotel, Bakersfield, California (J. A. Hugus, Western Gulf Oil Co., 900 Wilshire Blvd., Los Angeles 17, California)

17–18 Permian Basin Geophysical Society—and West Texas Geological Society, Exploration Meeting, Midland, Texas (Maxey Pinson, Union Oil Co. of Calif., 619 W. Texas, Midland, Texas)

23–25 Acoustical Society of America, New York, N. Y. (Wallace Waterfall, 57 East 55th St., New York 22, N. Y.)

September

3–14 International Union of Geodesy and Geophysics, Eleventh General Assembly, Toronto, Ontario, Canada (Dr. J. A. Jacobs, 49 St. George St., Toronto, Ontario, Canada)

October

24–26 Acoustical Society of America, Ann Arbor, Michigan (Wallace Waterfall, 57 East 55th St., New York 22, N. Y.)

November

7– 8 Pacific Coast Section SEG, Autumn Meeting, Ambassador Hotel, Los Angeles, California (J. A. Hugus, Western Gulf Oil Co., 900 Wilshire Blvd., Los Angeles, Calif.)

11–14 Society of Exploration Geophysicists 27th Annual Meeting, Statler-Hilton Hotel, Dallas, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

December

26–31 American Association for the Advancement of Science (Raymond L. Taylor, AAAS, 1515 Massachusetts Ave., Washington 5, D. C.)

1958

October

13–16 Society of Exploration Geophysicists, 28th Annual Meeting, Hotel Gunter, San Antonio, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1959

November

9–12 Society of Exploration Geophysicists, 29th Annual Meeting, Biltmore Hotel, Los Angeles, California (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

* * * * *

July 1, 1957 to December 31, 1958

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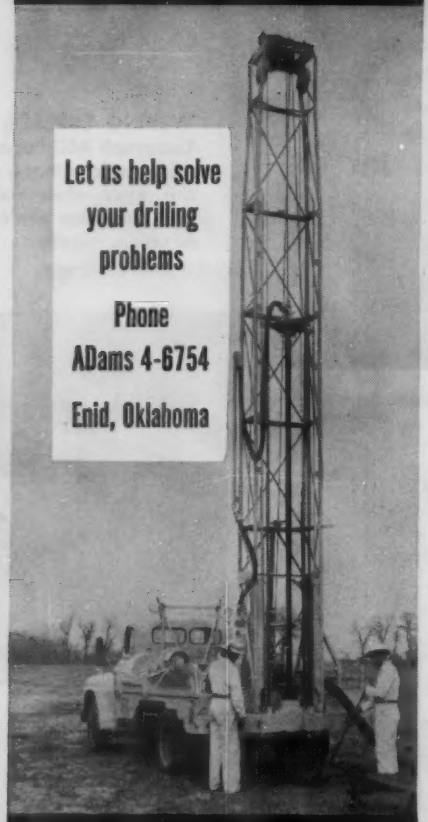

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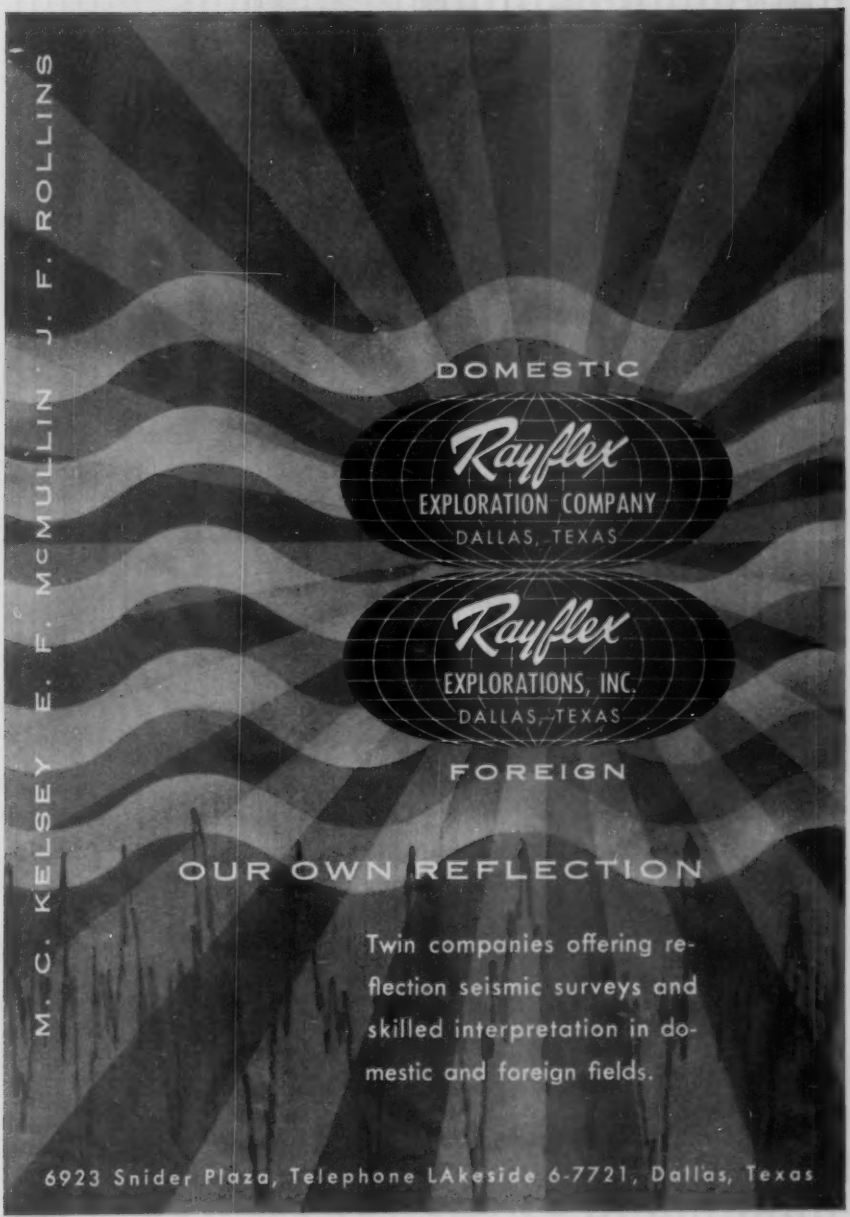
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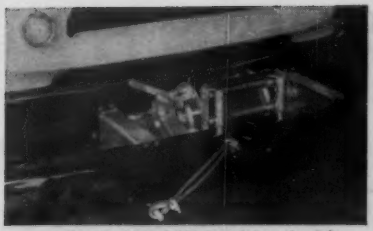

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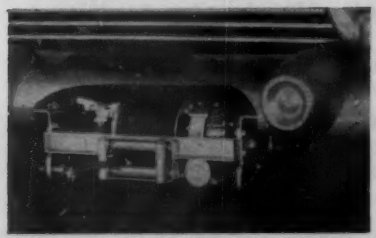

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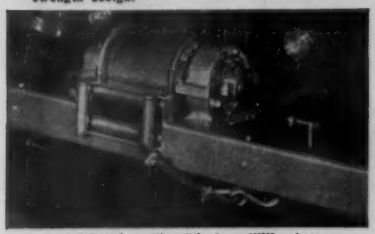

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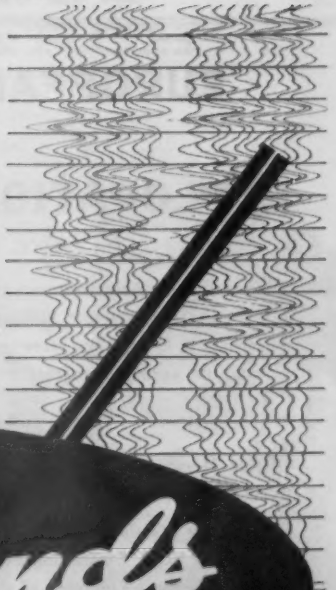

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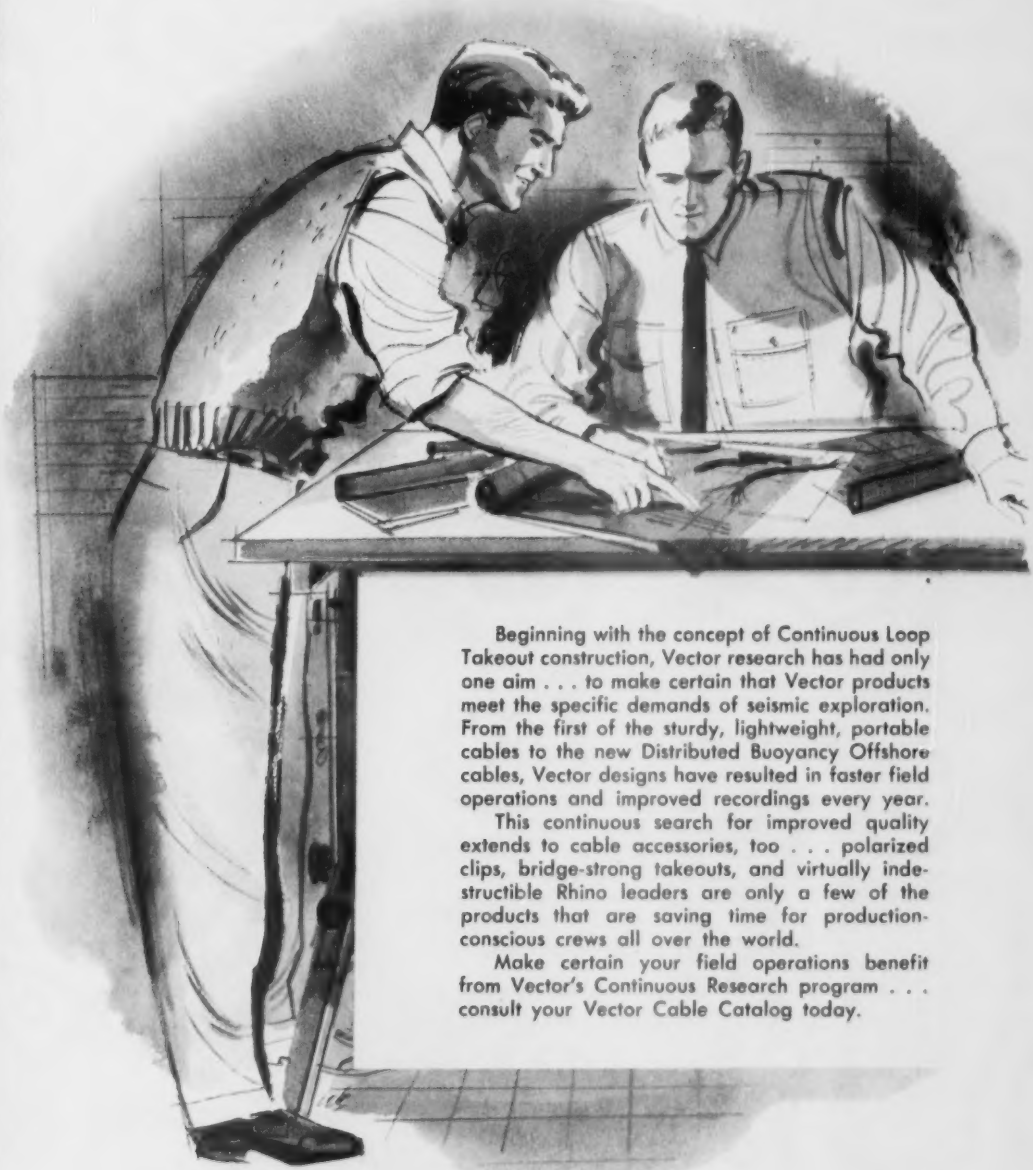

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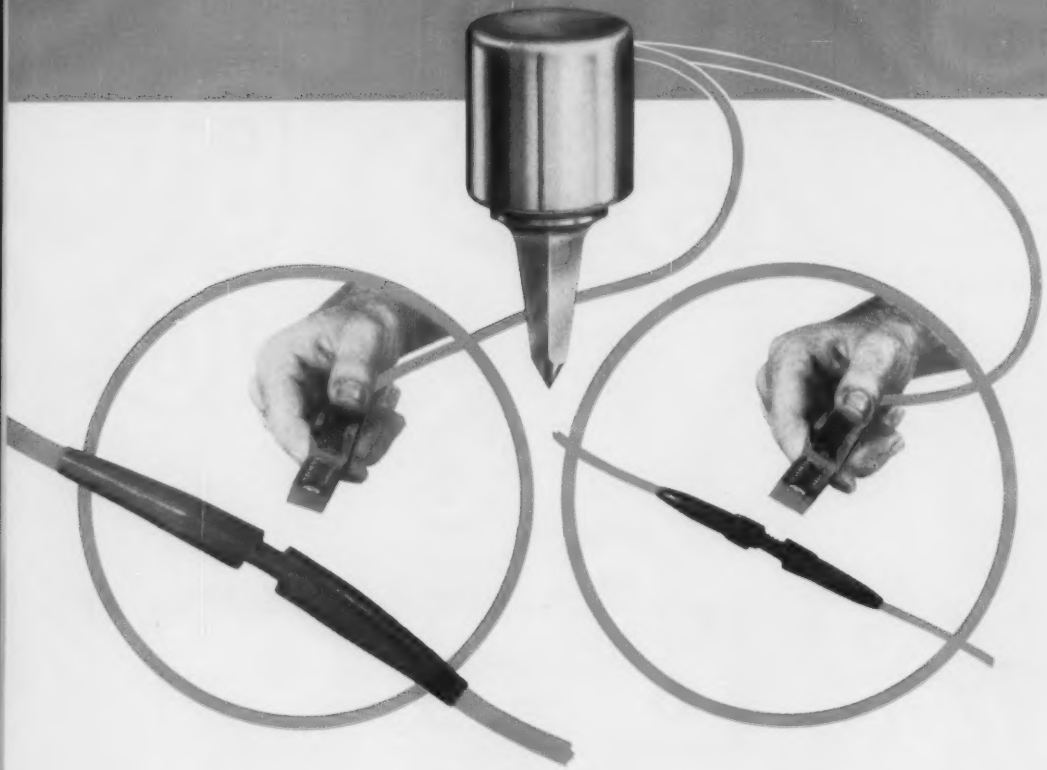

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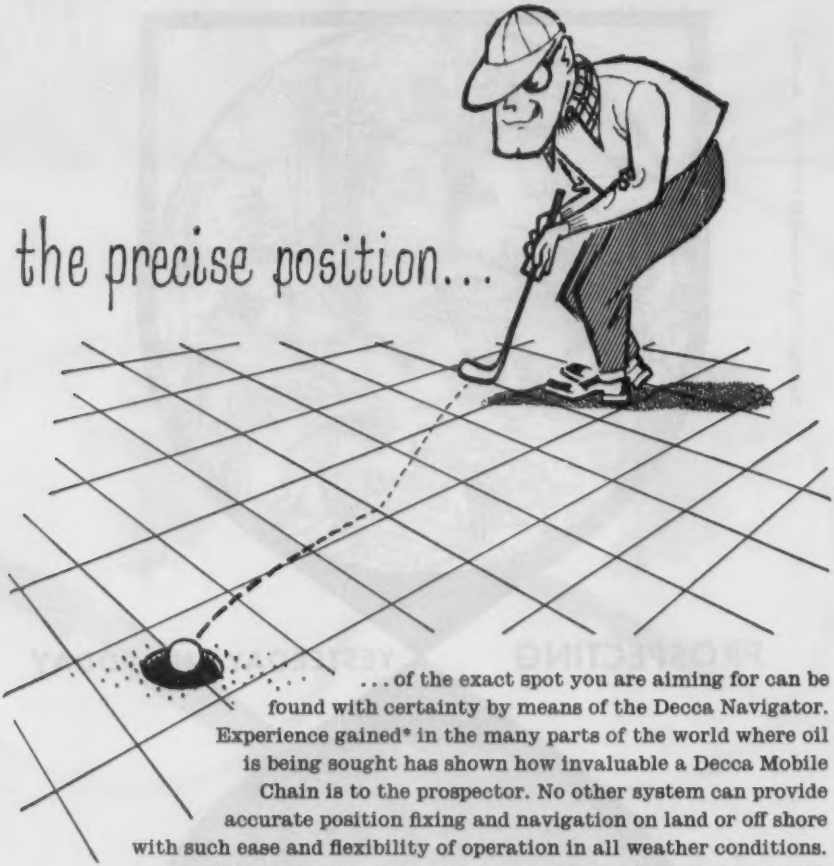

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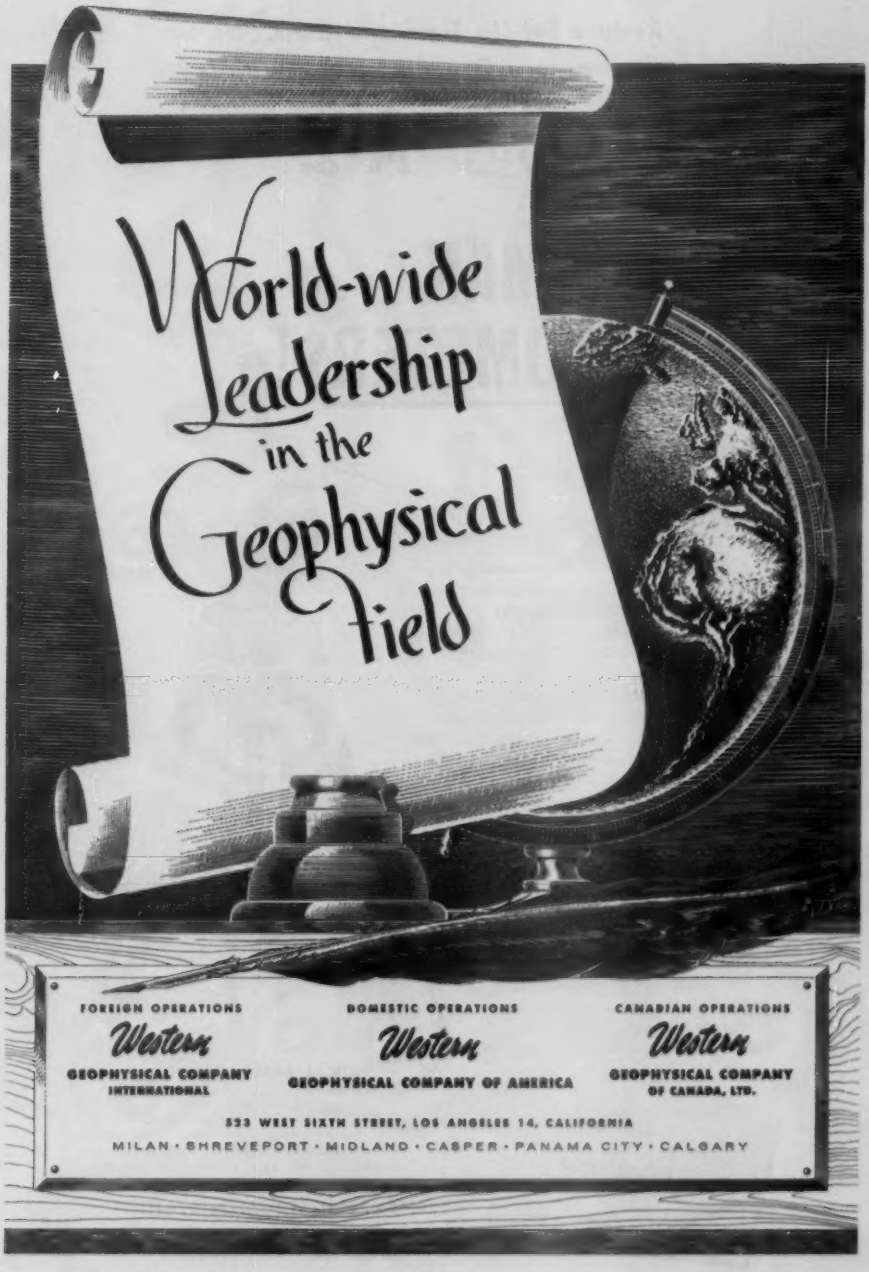
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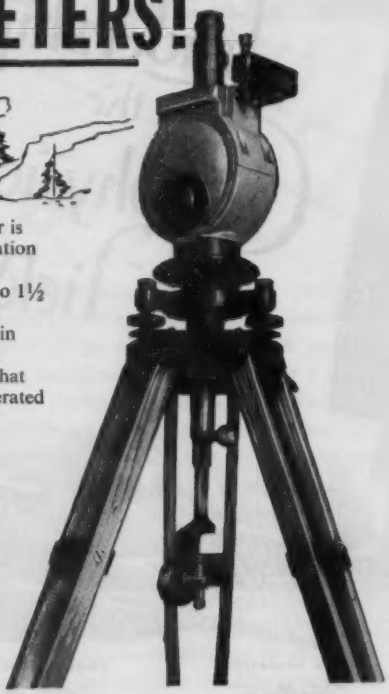

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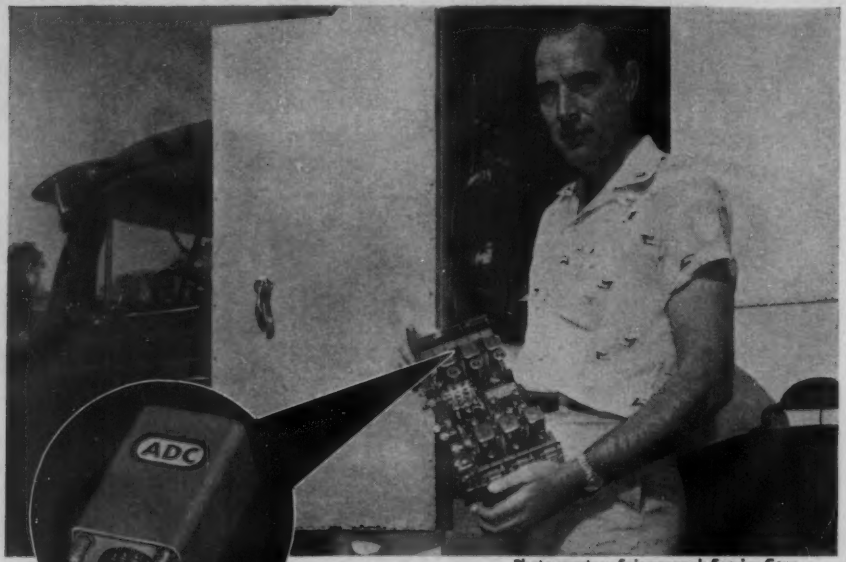

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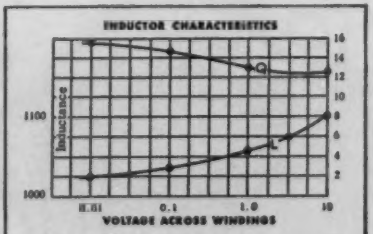
Write for descriptive data sheets, complete engineering specifications, electrical ratings.



Curve — shows Hi-Q, low frequency inductance, illustrating the unusual characteristics of these tiny units.

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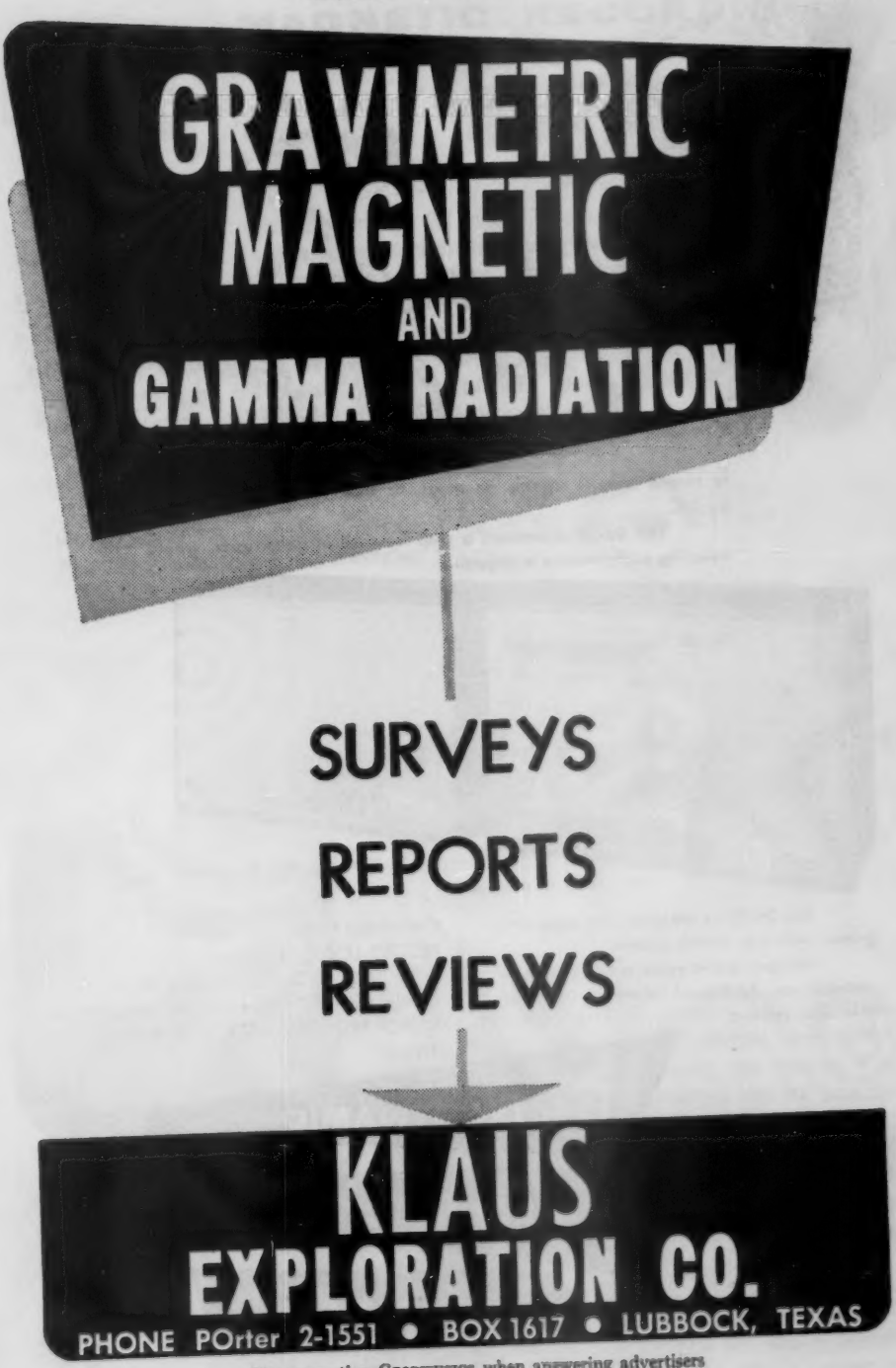
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to record seismic signals on magnetic tape has been developed by EIC.

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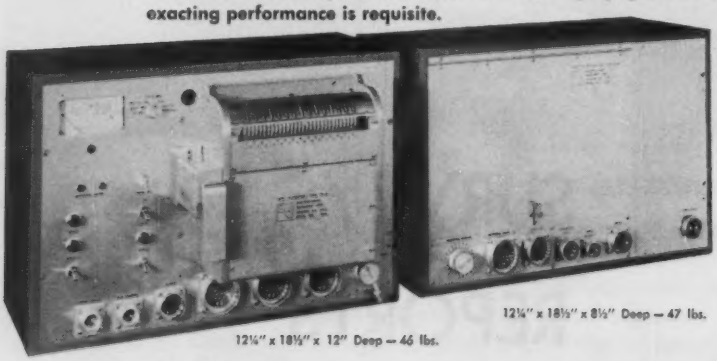

12¼" x 18½" x 12" Deep — 46 lbs.

12¼" x 18½" x 8½" Deep — 47 lbs.

The DR-30 is designed for easy integration with any seismic system.

Mil-spec sealed cases are available for portable use. Additional information is available upon request.

CHANNELS ● 24 Seismic; 6 Information.
RECORD LENGTH ● 6 Seconds.
FREQUENCY RESPONSE ● 5 cps to 500 cps.
SIGNAL-NOISE RATIO ● 50 db (RMS signal to RMS noise).
POWER REQUIREMENTS ● 15a @ 12v DC.

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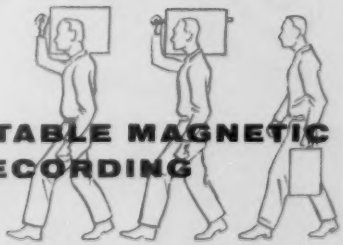
MAGNETIC RECORDING and ANALYSIS SYSTEMS

Here are some highlights from the SIE magnetic recording and analysis equipment program. To date, SIE has originated and is producing the most complete line of inter-related recording systems, tape transport devices, and data processing equipment available. Ranging from the compact PMR-7 Portable Magnetic Recorder for Direct Recording to the versatile MS-12 **GeoData** System, SIE magnetic instruments are designed to permit maximum flexibility in the choice of recording and analysis systems "tailor made" for the application. This program eliminates the purchase of equipment more elaborate than is necessary, and at the same time permits the addition of more complex recording and analysis instruments as required.

Whether your application requires a simple direct recorder or a complete office analysis system, be sure to contact SIE for full information when you plan your magnetic tape instrumentation program.



PMR-7 PORTABLE MAGNETIC DIRECT RECORDING SYSTEM

Three men can carry the complete PMR-7 Portable Direct Recording System including the 28 channel recorder, the PDA-2 Amplifier Unit, and the Power Supply. The recorder is available with fixed or movable head assemblies, and the records can be played back on an SIE Recorder or analysis system.

Designed for rough field duty, the PMR-7 utilizes magnesium and fibreglas construction for maximum strength in combination with light weight. Hermetic sealing of critical components, and water-tight case construction prevents moisture penetration even after submersion.

Judged by the toughest standards for field equipment: strength, durability and light weight; and meeting the famous SIE standards for recording accuracy and ease of operation, the PMR-7 meets every requirement of a modern seismic program.

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MAGNETIC RECORD ANALYSIS SYSTEMS

SIE manufactures office playback and magnetic record analysis systems to cover a wide range of applications. Among the tape-transport systems used in these applications are the MR-5 twin-drum recorder and the MR-7 and MR-9 three-drum recorders. The design program behind these instruments has been planned to provide units which can be used separately or in groups depending on the application. This policy permits continuous development of new equipment which can be used with previous units, and enables users of SIE instruments to maintain greater flexibility in organizing their data processing equipment investment programs.

The MS-12 GeoData System, the most elaborate of these systems, provides time cross-sections, and normal moveout and weathering-elevation corrections, in addition to many other interpreting operations. Other Recorders and interpreting equipment are combined for office or field playback. Contact SIE for full information regarding these instruments and how they can be combined to provide a custom designed installation to meet all of your analysis equipment requirements.

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GeoData

SYSTEM

MODEL MS-12

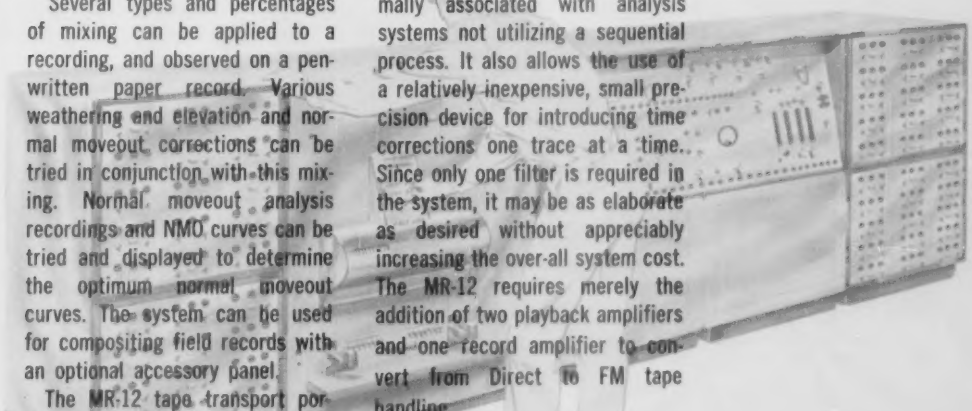
The MS-12 **GeoData** System processes FM and Direct recordings. It provides a record cross-section which is pen-recorded on paper and can be photographically reproduced. Cross-sections can be isopached or set to a desired reference plane. The graphically presented information is also permanently stored on magnetic records.

Magnetic or visual records which have been trace-mixed, filtered, corrected for weathering, elevation, and normal moveout can be made with **GeoData** equipment. Filter analysis may be made of field records by playing the same record back through several filters and displaying it as a pen-written paper recording.

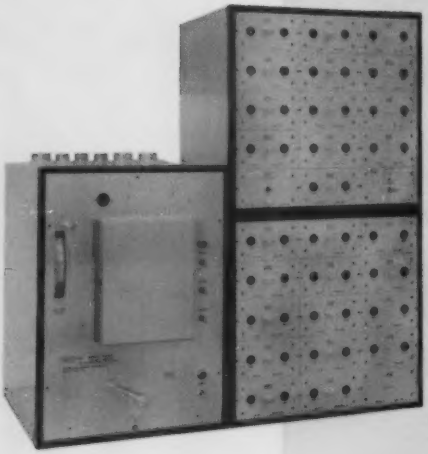
Several types and percentages of mixing can be applied to a recording, and observed on a pen-written paper record. Various weathering and elevation and normal moveout corrections can be tried in conjunction with this mixing. Normal moveout analysis recordings and NMO curves can be tried and displayed to determine the optimum normal moveout curves. The system can be used for compositing field records with an optional accessory panel.

The MR-12 tape transport portion of the MS-12 **GeoData** System consists of one field tape drum, one transfer tape drum and a wide cross-section plotter drum, all mounted on a common-driven shaft. The two standard SIE magnetic drums have adjustable combination FM and Direct recording head banks. The third drum is a 24-in. oscillographic drum for pen recording. Two galvanometer pen writers are provided for this visual display unit. One of these pens utilizes 2" of the oscillographic drum for monitoring purposes to observe time break, 100 cps reference signal and other information. The second galvanometer pen is used to display signal channels. The pen movement is adjustable to provide any desired horizontal scale for making cross sections.

The system is entirely sequential in operation in that it transcribes one trace at a time from the field tape, to either the transfer drum or the paper drum. This eliminates most of the many electronic amplifiers which are normally associated with analysis systems not utilizing a sequential process. It also allows the use of a relatively inexpensive, small precision device for introducing time corrections one trace at a time. Since only one filter is required in the system, it may be as elaborate as desired without appreciably increasing the over-all system cost. The MR-12 requires merely the addition of two playback amplifiers and one record amplifier to convert from Direct to FM tape handling.



The MS-12 **GeoData** System provides an unchallenged achievement in providing application flexibility for every interpretation and analysis program. For full details, contact SIE or your nearest representative.



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The MR-4 and MR-8 are only two of the SIE magnetic recording systems available for every application in the field or office. Today, more than 60 complete SIE magnetic systems are in operation and have established the Standard of the Industry in magnetic instrumentation.

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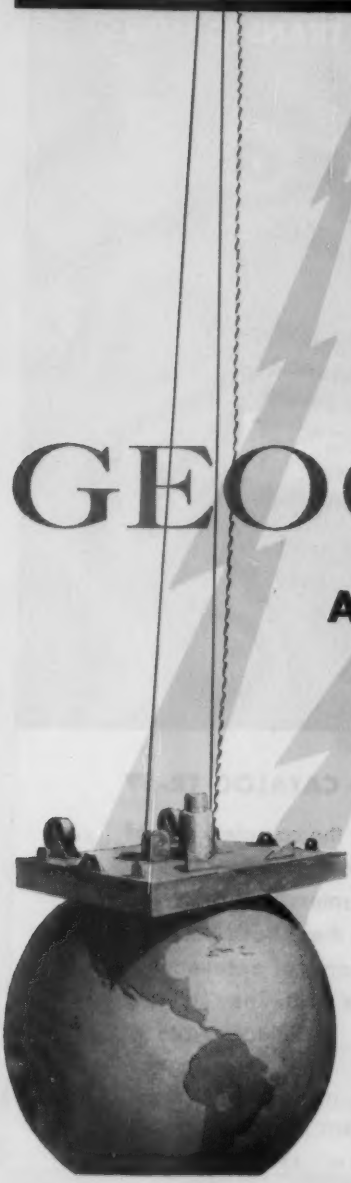

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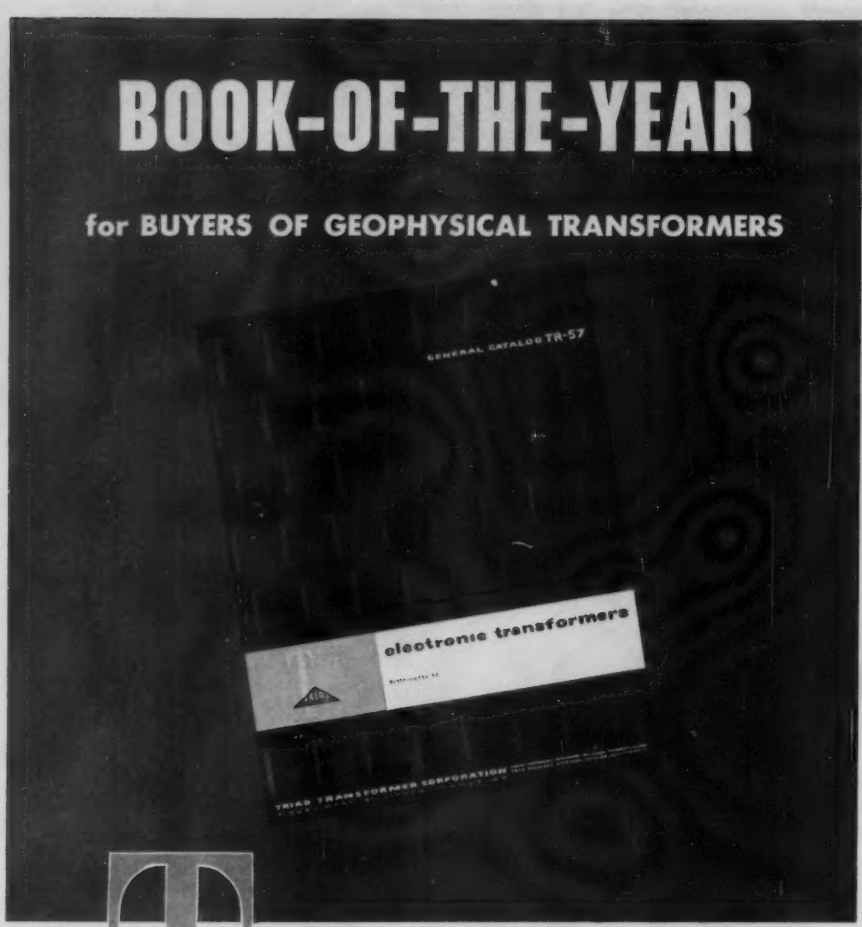

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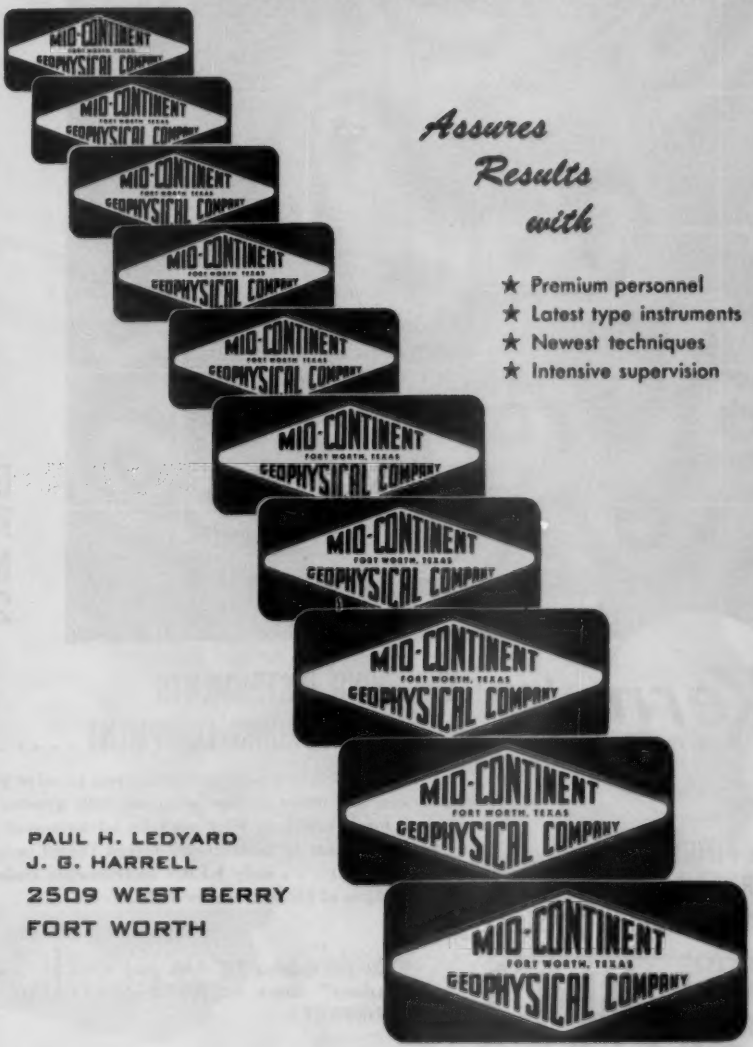

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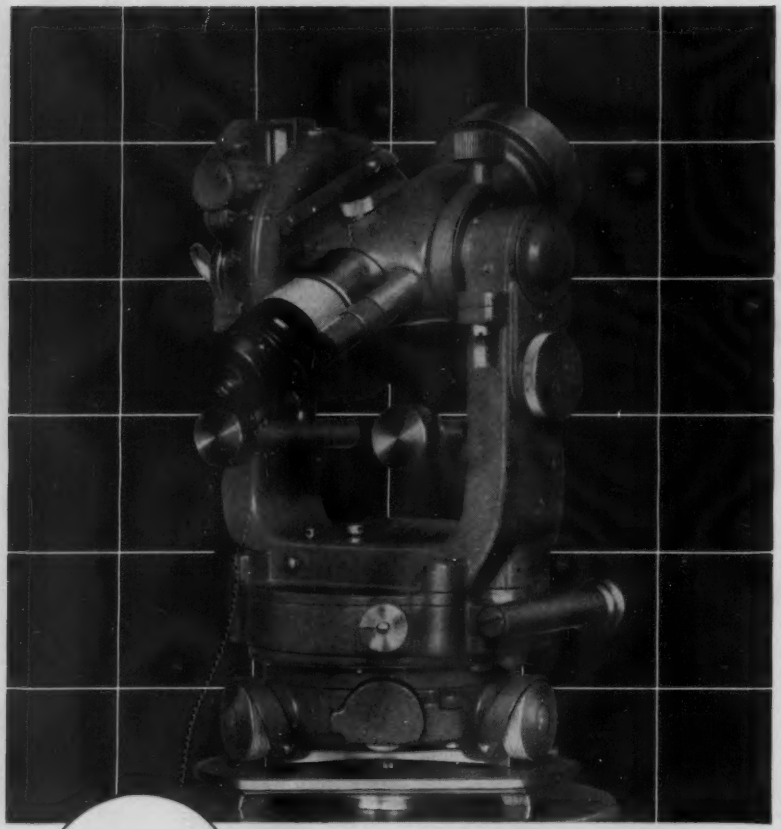

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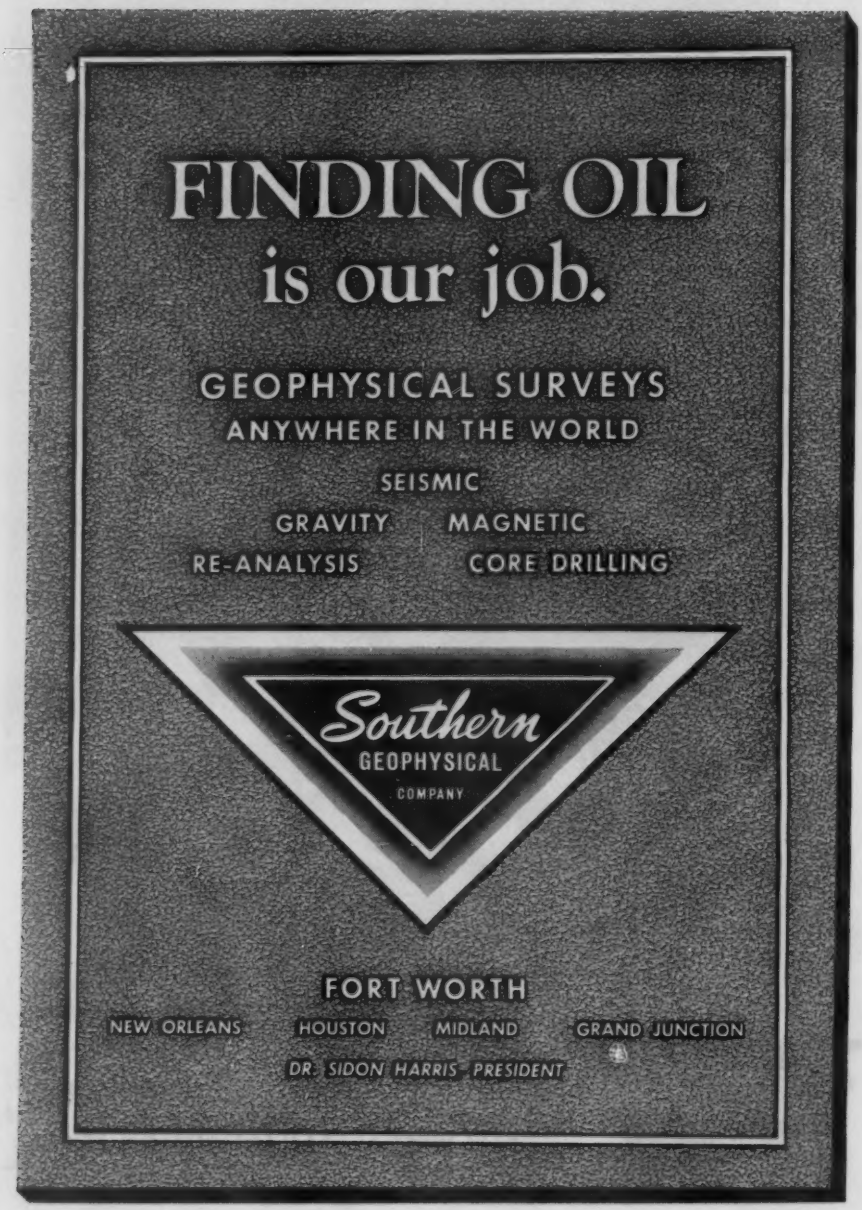
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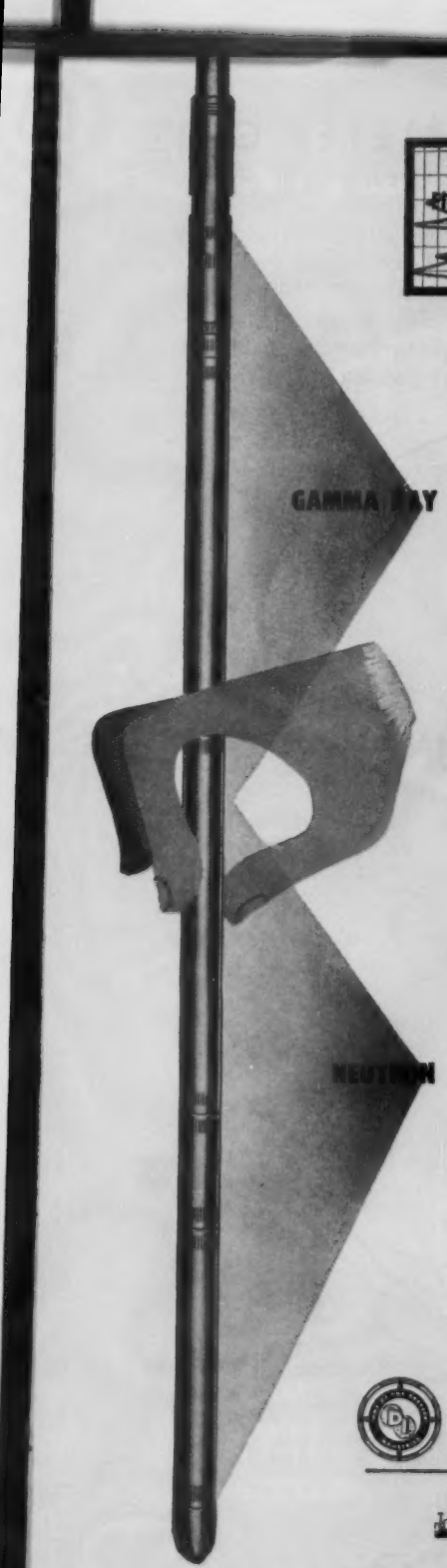

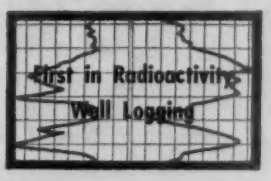

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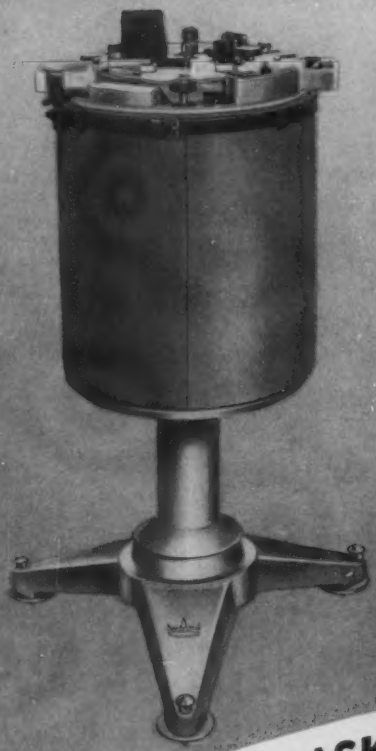

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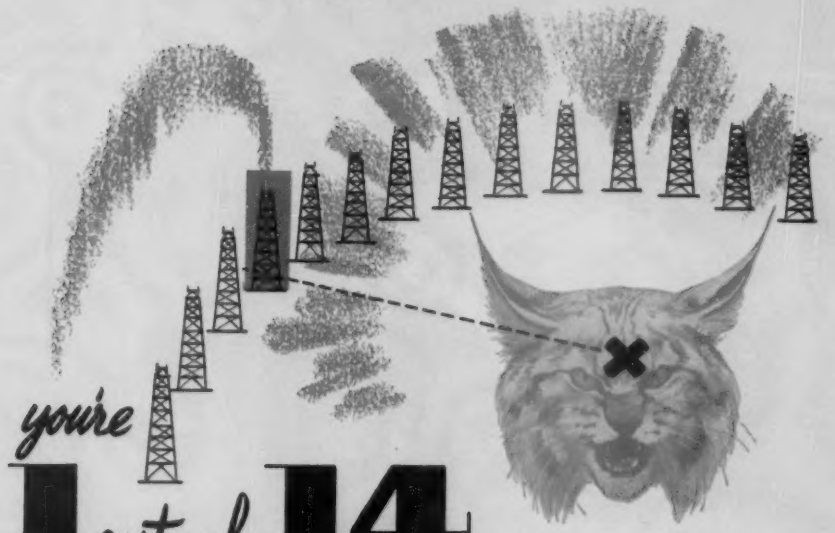

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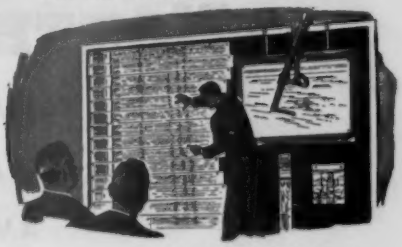

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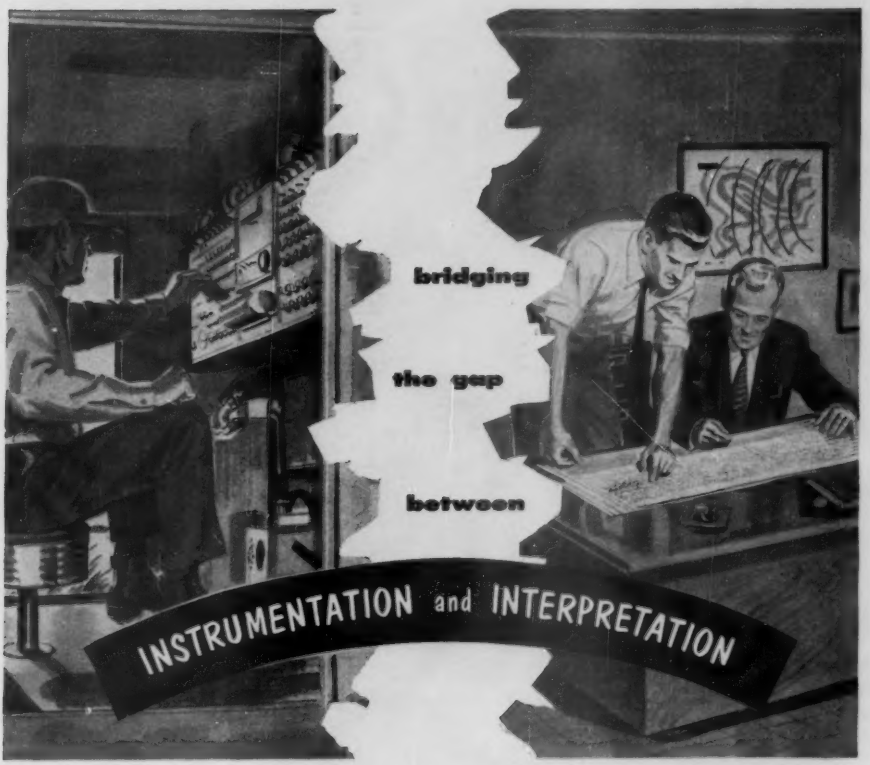

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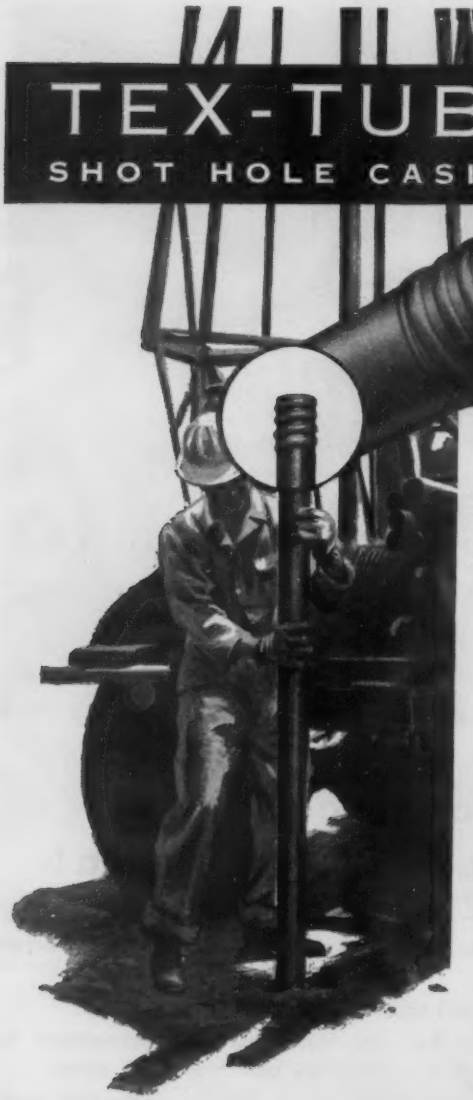

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How would you go about defining the boundaries of oil concessions in the dense jungle of Guatemala? Fifteen major oil companies are doing it with a Shoran-guided AERO survey . . . and getting important airborne magnetometer data, as well, for ten million previously unmapped acres.

AERO crews, packed in by mule and supplied by air drop, have set up Shoran towers on mountain tops. Shoran will guide the survey plane and provide positional information for defining the concessions. This employs Shoran experience gained by AERO over the Liberian jungle, over the frozen North, and the Middle Eastern desert.

Whenever exploration begins—in western Canada, Mozambique, the Middle East, Philippines or anywhere in the world—the first step in mapping or geological reconnaissance is the AERO survey. Let our engineers show you why.

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For "a hole in one," your best bet is the accurate and dependable interpretations of GRAVITY SURVEYS. Based on practical application of the latest proven scientific methods, you can benefit from our broad experience and acquaintance with oil provinces throughout North America.

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WE WEIGH THE EARTH

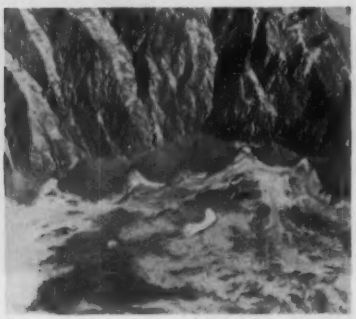
Can you identify these areas?

The photos below were taken by Fairchild aerial photo crews during routine survey flights.

More than material for a guessing game, they demonstrate the various services provided by Fairchild: magnetometer surveys for the geologists; detailed photo-maps for the city planner; and topographic maps for the civil engineer. All of them have learned that when aerial surveys are needed fast, and must be right the first time, they can depend on Fairchild.

1.

2.



3.

4.

1. Rangely Anticline, Rangely, Colorado
2. Jetty construction, Jones Inlet, Long Island, N. Y.
3. Death Valley, California
4. Long Beach Harbor, Long Beach, California

The next time you consider a survey job, get the Fairchild story. Often, aerial surveys can save 50%, or more, in time and money.

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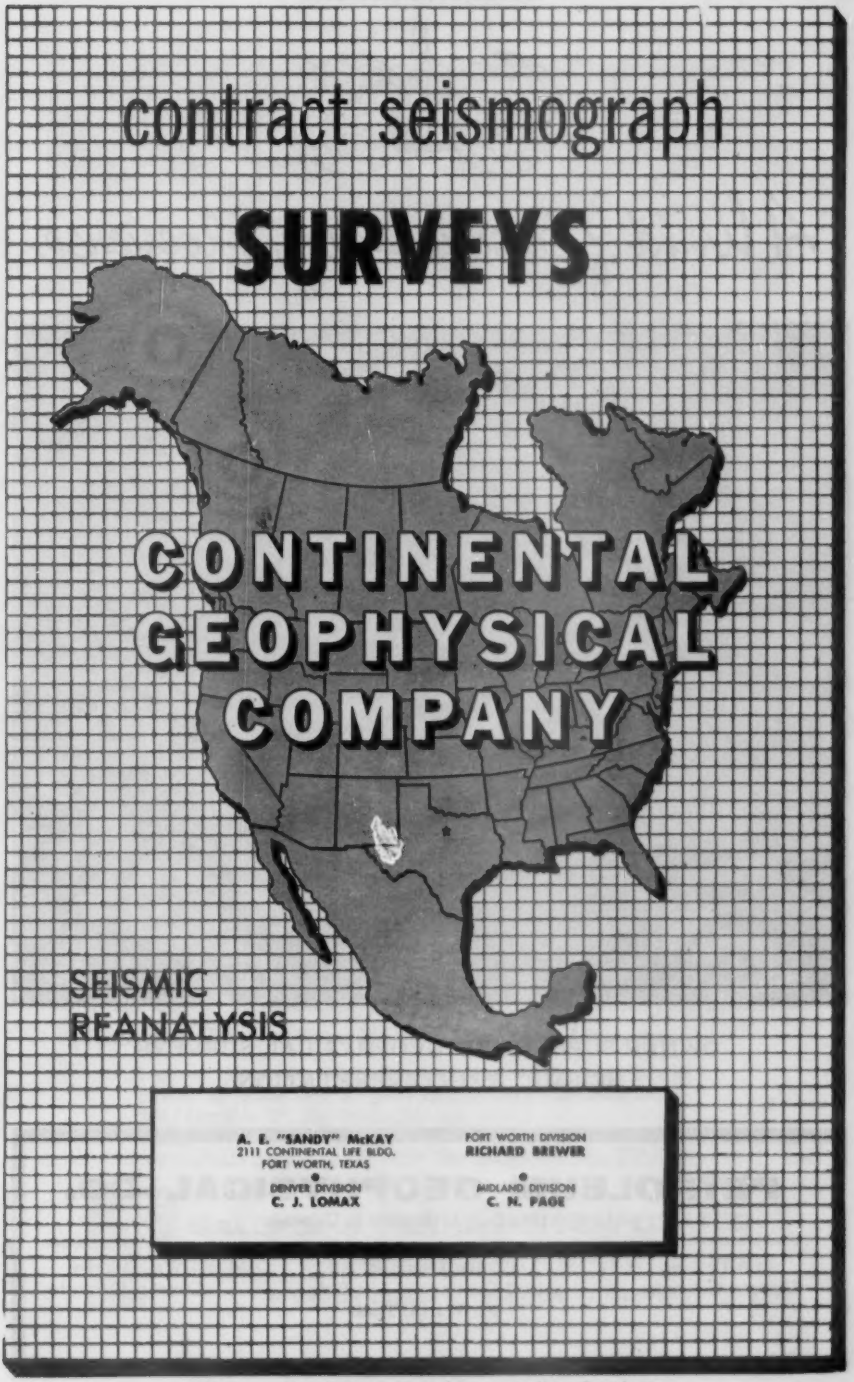

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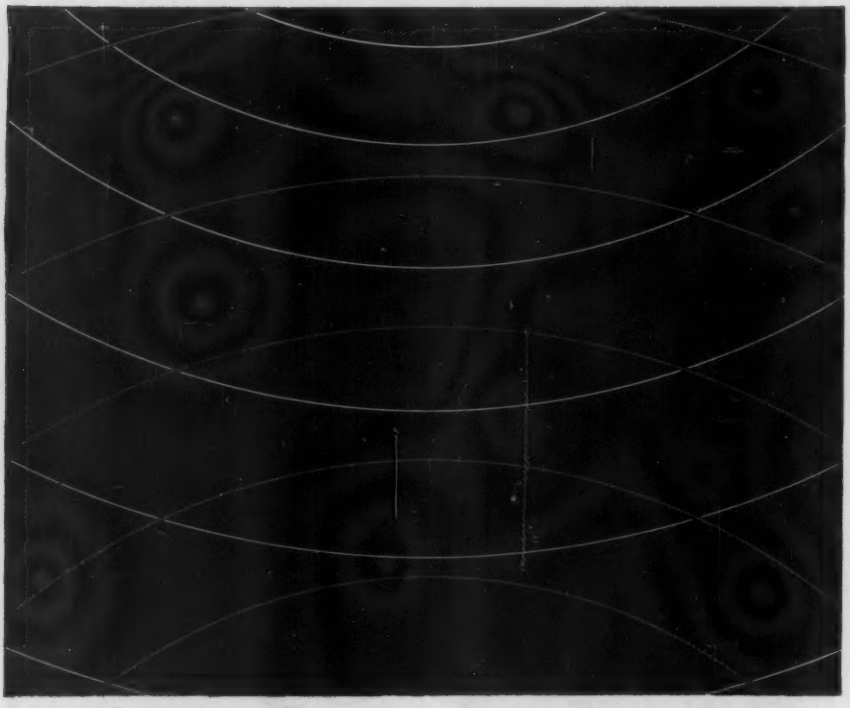
A World of Seismic Survey Experience



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Field party on survey for proposed Canyon Dam on Texas' Guadalupe River.

TYPE FA-176

W&T SURVEYING ALTIMETERS SPEED HYDROLOGIC STUDY OF RESERVOIR BASIN

A ground-water and geologic survey, involving water table isograms for 400 square miles adjoining the proposed Canyon Dam Reservoir on Texas' Guadalupe River, recently was completed in 35 days. Despite difficult terrain and maximum relief of 1000 feet, over three hundred spot elevations were taken during this period. The speed with which this work was done is attributed to the use of the two-base method of altimetry employing three Wallace & Tiernan Type FA-176 Surveying Altimeters.

Technical data on the FA-176 Altimeter include: **Range** — any interval of 2000′ up to max. limit of 5000′; **Accuracy** — 2.0′; **Sensitivity** — 0.5′; **Scale Length** — 20″; **Dial Size** — 8½″ dia.

For details on FA-176, send for Bulletin No. TP-7-A

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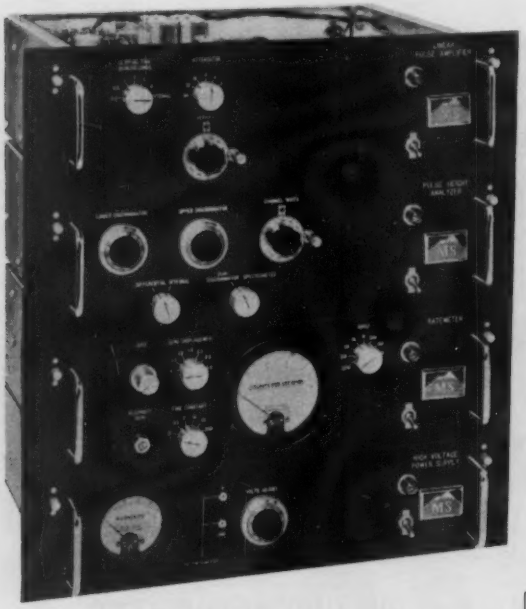

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NEW MODEL SR300

Mt. Sopris Radiation Spectrometer

A basic instrument with many field and laboratory applications in Geophysics.

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Correlation of sediments based on direct radiometric measurements of potassium, thorium and uranium content.
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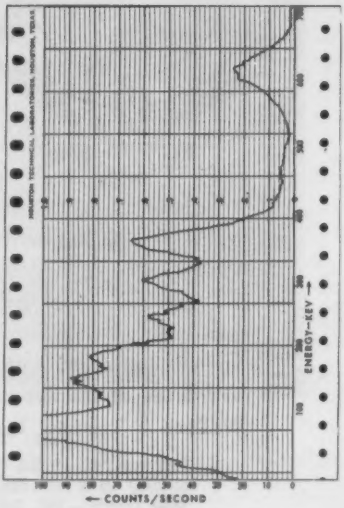
Restricted energy—band counting in dating and assay applications.
Determination of radium-potassium ratios of anomalous areas in petroleum exploration studies.
X-Ray fluoresence spectrum analyzer.
Determination of uranium-thorium ratios for sedimentation environment investigations.
Neutron—gamma spectrum analyzer.

The SR-300 is smaller and more compact than comparable equipment, and it is rugged enough for use in the field.

Each of the units . . . pulse amplifier, pulse height analyzer, rate meter and power supply . . . may be used independently.



For further details, write...

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Galileo and the fundamentals of gravity!

Galileo Galilei (1564-1642) was the first to refute Aristotle's teachings that the acceleration of falling bodies was in direct ratio to their weight. Best known because of the tremendous row they produced were Galileo's experiments at the famous Leaning Tower of Pisa. These experiments, however, were not the primary ones. They were offered as confirmation of many previous deductions which proved that the rate of acceleration of falling bodies is a constant and not a function of mass.

Galileo ingeniously used the incline plane to slow down the falling motion of heavier bodies, without changing the general character of the motion. And having no clock, he devised a tank of water with a hole that could be opened and closed with the finger. Measurement of the amount of water that ran out during a certain distance traversed by the falling body was taken as the measure of the interval. Thus, Galileo was able to deduce that the velocity of a falling body increases exactly as does the time that it has been falling.

Even as a student of 18, Galileo enunciated the law of pendular motion. He observed while watching the swinging lamps in the church at Pisa, and counting his pulse, that the time of swing in a pendulum is constant regardless of the length of oscillation.

Today, the geophysical unit of gravity measurement is the gal, named after Galileo. And the most popular instrument for gravity measurement is the compact, lightweight Worden Gravity Meter, which requires no external power source and has a reading accuracy of 0.01 milligal.

For free 14" x 9" Galileo print suitable for framing, send your request to Department D...

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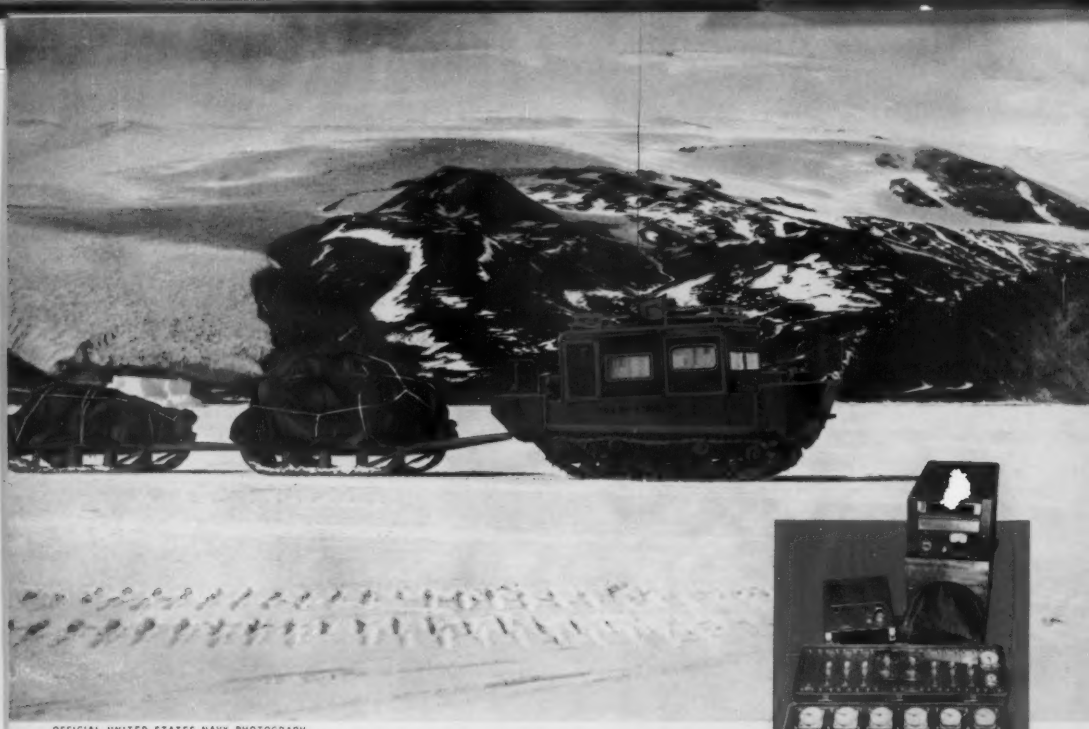
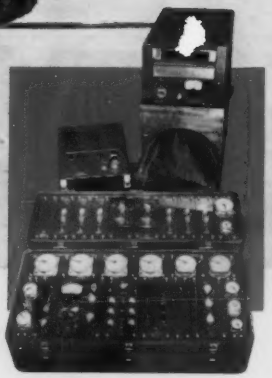


OFFICIAL UNITED STATES NAVY PHOTOGRAPH

7000B Seismographs selected for International Geophysical Year

U. S. ANTARCTIC PROGRAMS



7000B Portable Seismograph showing RS-8U camera, dynamotor, control panel, and one bank of six amplifiers (IGY systems have four banks of six amplifiers, or 24 traces).

GLACIOLOGISTS of the United States National Committee recommended the "all purpose" seismic systems, developed by Texas Instruments Incorporated, as the best suited to exploit seismograph techniques in glaciological study during the IGY program. For this important program, operational versatility, accurate performance, and rugged dependability were the governing criteria in equipment selection.

The 7000B "all purpose" system offers three seismographs in one—a frequency range of 5-500 cps with a flip of switches. The VLF or Refraction Seismograph included in the 7000B will be used primarily to determine the velocity variations of the seismic waves in the ice sheet. The HR High Resolution Reflection Seismograph will provide accurate data on the stratigraphy and structure of the glacier and near-surface formations, while the Conventional Reflection Seismograph will supply useful deep information from the sub-glacial floor. All three methods will utilize the many filtering variations available in the 7000B to obtain the optimum signal-to-noise ratio of desired impulses.

Since each seismic traverse party will operate as a self-sufficient unit, the low maintenance reputation of the 7000B Seismograph was also an important factor in its selection. And needless to say, these seismic systems will be subjected to extremely exacting operating conditions in the Antarctic—conditions that will ask the most of equipment and men.

Texas Instruments Incorporated is proud that under circumstances where *quality* counts most, the USNC glaciologists selected 7000B Seismographs.

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a Seismotron system

Printed in U.S.A.

History of the Seismograph
Number 2 in a series.

Microseismic disturbances *studied with vertical pendulum!*

Francisci Travagini, 1679, appears to be the earliest writer who believed that an earthquake is a pulse-like motion propagated through solid ground. He devised a pendulum whose tip terminated in loose sand or ash which would describe trails in the sand associated with the movement of the earth.

However, Father Timoteo Bertelli, 1870, of Florence is credited with being the founder of systematic microseismical research. Depicted here is Bertelli making observations through his Normal Tromometer. This instrument (shown in cutaway drawing) consisted of a vertical pendulum 1½ meters long carrying, by means of a fine wire, a weight of 100 grams. To the base of the bob a vertical stile is attached, and the whole is enclosed in a tube, terminated at its base by a glass prism which permits viewing the stile in any azimuth. Inside the microscope a micrometer scale is so arranged that it can be turned to coincide with the direction of oscillation of the stile. In this way Bertelli made 5,500 observations on both the amplitude and azimuth of microseismic motions.

Modern microseismic recordings are made most efficiently on the magneDISC, disc-type magnetic recorder, an exclusive *Seismation* system developed by Texas Instruments Incorporated. The magneDISC, with its greater capacity for recording, storing and reading back of valuable seismic data, is used by leading seismologists the world over in their relentless search for oil.

For free 14" x 9" Bertelli print suitable for framing, send your request to Department D...

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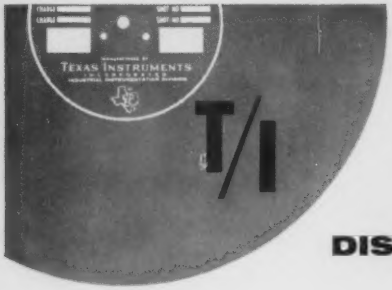
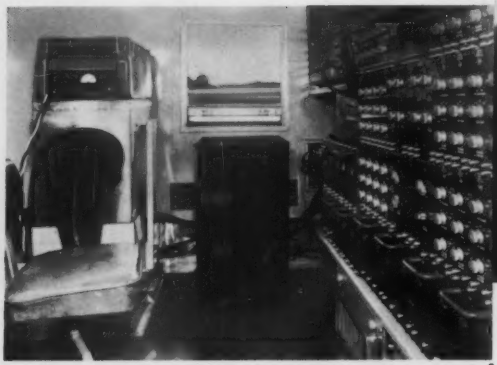


magneDISC*

DISC-TYPE MAGNETIC RECORDER



Best in the Field!

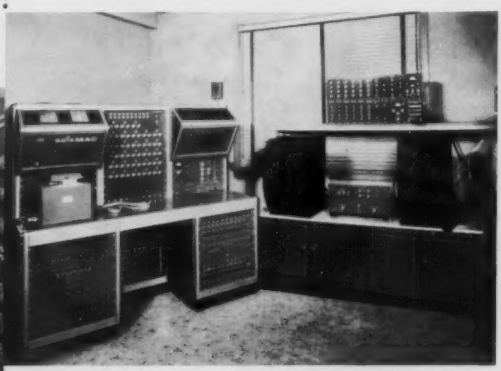
The magneDISC has proved its operational superiority in exacting seismic data recording conditions throughout the world.

Greater Capacity—Record up to 115 data and auxiliary traces at one time.

Reliable and Rugged—No pampering required . . . no air-conditioned, dust-free, humidity-controlled environment is needed for accurate performance of the magneDISC.

No "Barber-Poling"—The disc is the most stable geometric design for magnetic recording . . . no skewing of tape to affect accuracy.

Recording Heads stay in precise alignment—discs can be played interchangeably on any magneDISC—tolerances are maintained to insure timing accuracy of ±½ millisecond trace to trace.



Best in the Central Processing Office!

The versatility of the magneDISC is unsurpassed in the CPO, used in conjunction with the seisMAC for automatic data reduction.

Speed of Processing—utilizing two 115 head magneDISC Transducer Units, data may be played from one through the seisMAC and re-recorded on the other in one continuous operation.

Greater Operational Latitude—two T/D Units provide 230 channels of information for mixing, compositing, or stacking as desired—no necessity for synchronization of several drums as with other systems.

Easier Handling and Storage—one movement of lever accurately positions disc in the T/D Unit—eject button pushes disc out for easy removal. magneDISCS take up less storage space than any other type of magnetic recording medium.

For complete information and the many other advantages of the magneDISC, write for Bulletin DS-307; or request a visit from the TI representative!

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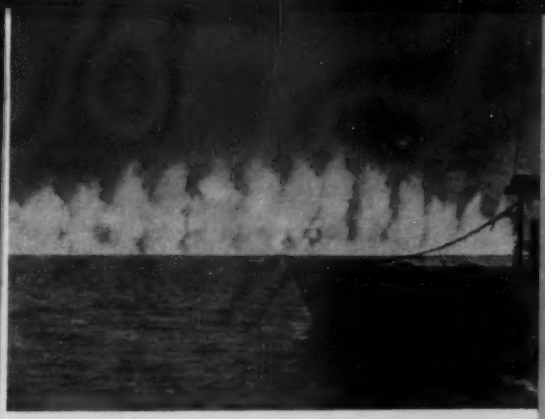
* a Seismation system ®

7090



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Which record would you interpret with confidence? Records (A) & (B) were shot out of the same hole—with the same spread length and location. Record (B) clearly demonstrates the superiority of Petty's patented "Vari-Pattern" technique.

Ordinary pattern shooting is not new to geophysical exploration. But Petty's exclusive "Vari-Pattern" process is new, and is obtaining consistently better data in many previously recognized poor record areas.

Essentially, Petty's "Vari-Pattern" technique reduces the effect of unwanted surface traveling waves and reinforces desired reflections. This is accomplished by appropriate variation of the sensitivities of geophones, and sizes of charges used in multi-unit patterns.

Petty's "Vari-Pattern" method is now being used for more economical oil exploration in many diverse areas. Decide now to put such unique modern methods—and the experience of this oldest exploration company—to work for you.

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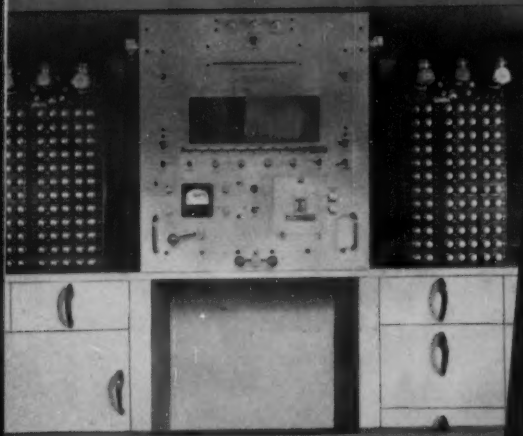
THE BRUSH MAGNETIC RECORDING SYSTEM



Model TR-2 Magnetic Recorder-Monitor

THE BRUSH TWENTY-FOUR CHANNEL RECORDER, FOR TRUCK OR BOAT MOUNTING, CONSISTS OF:

MODEL TR-2 MAGNETIC RECORDER-MONITOR

- Twenty-eight channel tape-on-drum recorder.
- Galvanometer style viewing monitor system — for monitoring before and during shooting.
- Direct writing permanent record monitor system, with built-in seismic filters.
- 100 cps timing signal channel.
- Noise cancellation channel (optional use).
- Two information channels (up-hole, time break).
- Twenty-four signal channels.
- Speed lock system for high positional stability.
- New rigid belt drive system for tight, smooth tape movement.

Brush offers a choice of two Amplifier Modulator systems: The Model AM-2 combination Amplifier-Modulators and the Model 721 Seismic Amplifiers with separate Modulator Units. Also, the Recorder and Modulators can be used with any good broad band seismic amplifiers which you may now have available.

MODEL AM-2 AMPLIFIER—MODULATOR UNITS AND CONTROL PANEL

- Twenty-four channels of combined broad band seismic amplifier and frequency modulator.
- Variable soft filtering, for eliminating excessive ground roll or high frequency disturbance.
- Standard high quality seismic amplifier gain, AGC, suppression, line balance, and test features.
- Standard high quality seismic amplifier control panel with trip, suppression control, by-passed first breaks, and test features.

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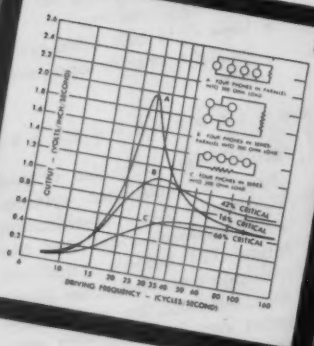
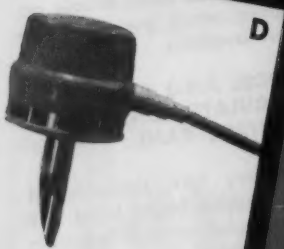
A

B

C



D



E

THE BRUSH 241 SERIES SEISMOMETERS

These Brush Seismometers furnish the highest energy output per pound of weight available in commercial units today. Of the standard accepted seismometers, only the 241 Series furnishes a complete line of these small, compact units. These high output phones, covered with thick plastic jackets have a history of an extremely low repair rate.

The Brush spike design gives intimate contact with the earth. It is an extremely effective coupling of the seismometer to ground.

Brush manufactures a complete line of 35 seismometers on three basic frequencies. With complete rubber moulding facilities, Brush can furnish complete cabled sets of seismometers in any multiples desired. Brush also has the facilities

A MODEL 241 SEISMOMETER BASIC UNIT

Diameter	1⅜"
Height	1⅝"
Weight	9 oz.

Stud ⅛" diameter. 20 thd. by ⅜" length for base attachment.

B MODEL 241-3C AND 3Y WELL SEISMOMETERS

Diameter	3⅛"
Length	15"
Weight	22 lb.

C OUTPUT VS. FREQUENCY 4 Model 241 Seismometers

K. Notes:

1. Natural undamped frequency ..... 25 cps.
2. Coil resistance ... 300 ohms.
3. Individual geophones are not shunted.

D MODEL 241-LP PLASTIC LAND SEISMOMETER

Diameter	2¼"
Height	2"
Weight	13½ oz.

E MODEL 240-L LAND SEISMOMETER

Diameter	3¼"
Height	2¼"
Weight	2½ lb.
Frequency	6 cps.

and ability to design special adaptations to meet any customer's needs.

The MODEL 241 SEISMOMETER BASIC UNIT is the High Output Basic Unit used in all models of Brush Seismometers. The standard frequencies are 15, 20 and 30 cps. Others may be supplied on special order. The frequency accuracy is held to within one cycle per second.

The matched load voltage sensitivity of a 300 ohm coil is 0.41 volts/inch/sec. The power output of any resistance coil into a matched load is 5.6×10^{-4} watts per (inch/sec.)^2.

The seismometer is housed in a case machined from solid brass bar stock. The leads are brought out through glass bead hermetic seals.

F MODEL 241-GL Gimbal SEISMOMETER

Diameter	2"
Length	8"
Weight	2¾ lb.

G MODEL 241-SH SHOT HOLE SEISMOMETER

Diameter	1⅜"
Length (including bail)	7½"
Weight	2 lb.

H MODEL 241-MP MARSH SEISMOMETER

Diameter	1½"
Length	7½"
Weight (brass)	1½ lb.
Weight (aluminum)	1¼ lb.

I MODEL 241-MH HEAVY MARSH SEISMOMETER

Diameter	1⅜"
Length	6¾"
Weight	2½ lb.

J MODEL 241-F FLOATING SEISMOMETER

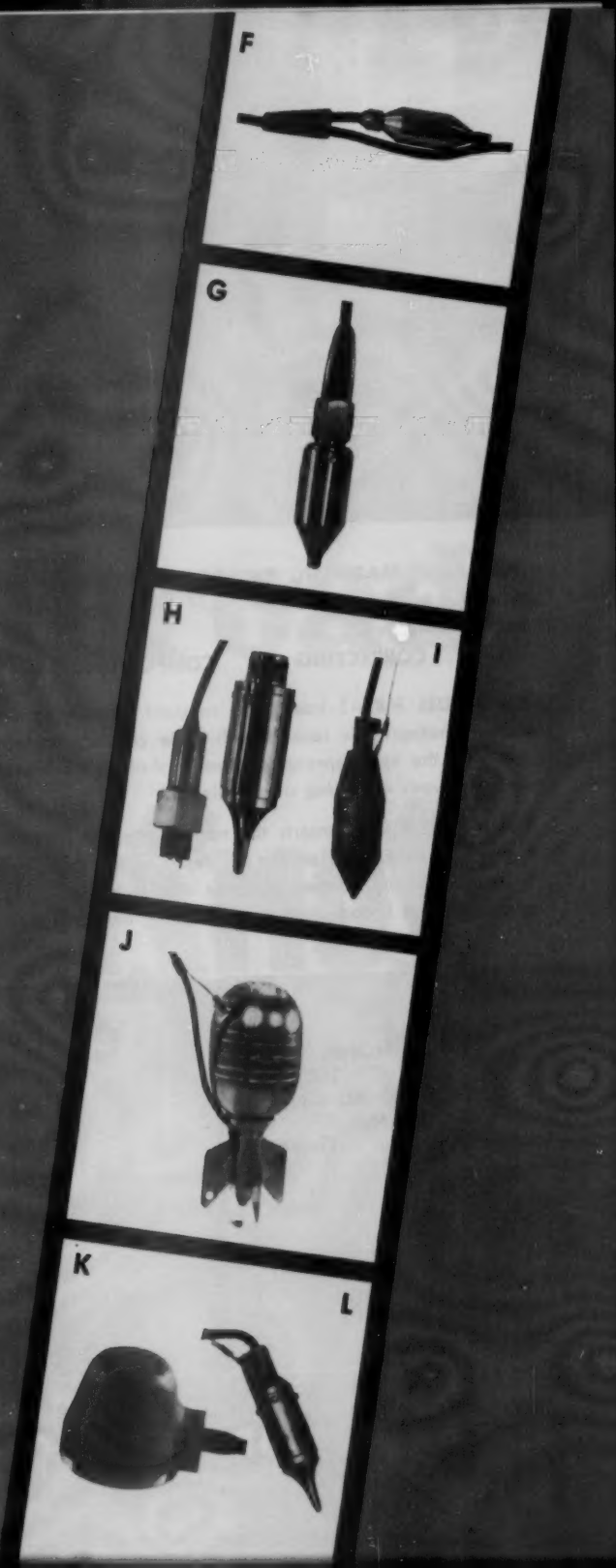
Diameter	5"
Height	12"
Weight	4½ lb.
(with damping fluid)	

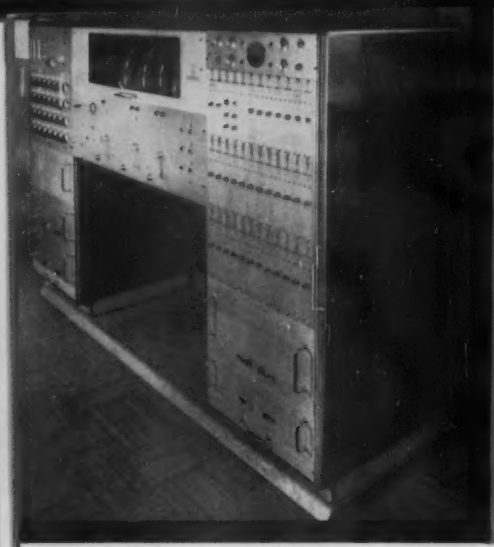
K MODEL 241-LH HEAVY LAND SEISMOMETER

Diameter	2¾"
Height	2¾"
Weight	24 oz.

L MODEL 241-ML LIGHT MARSH SEISMOMETER

Diameter	1⅜"
Length	6"
Weight	1¼ lb.





MAGNETIC RECORD ANALYZER

MODEL MRA-1 MAGNETIC RECORD ANALYZER — for fixed correction, compositing and reproducing.

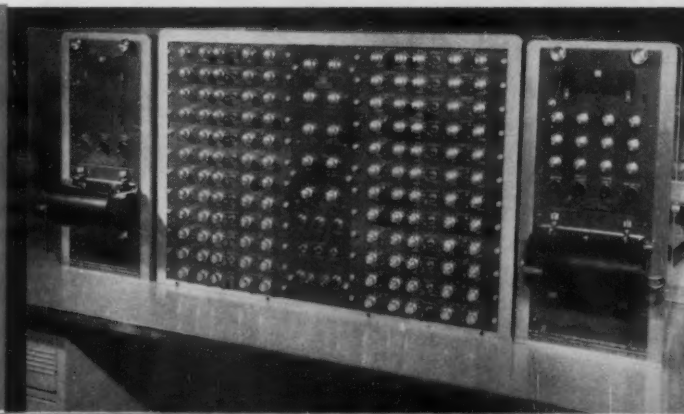
THE BRUSH MAGNETIC RECORD ANALYZER for central laboratory or field office use provides, for its end product, the visual photographic record of one or many field tapes — with these flexible features:

CORRECTING • COMPOSITING • FILTERING • MIXING

The MODEL MRA-1 inserts the constant weathering and elevation corrections. It provides time section photographic records with these constant corrections. It composites any number of tapes shot with the same spread and same shot hole (different depths). A broad selection of filtering and two types of mixing are available.

The MODEL MRA-2 inserts the variable stepout corrections as well as the constant corrections. It provides either time section or depth section photographic records with all corrections inserted. It composites any number of tapes shot with the same spread and different shot hole locations and depths. A broad selection of filtering and two types of mixing are available.

MODEL VFM-2 FILTER UNIT
Filters and mixes signals from the MRA-1 for the photographic oscillograph.



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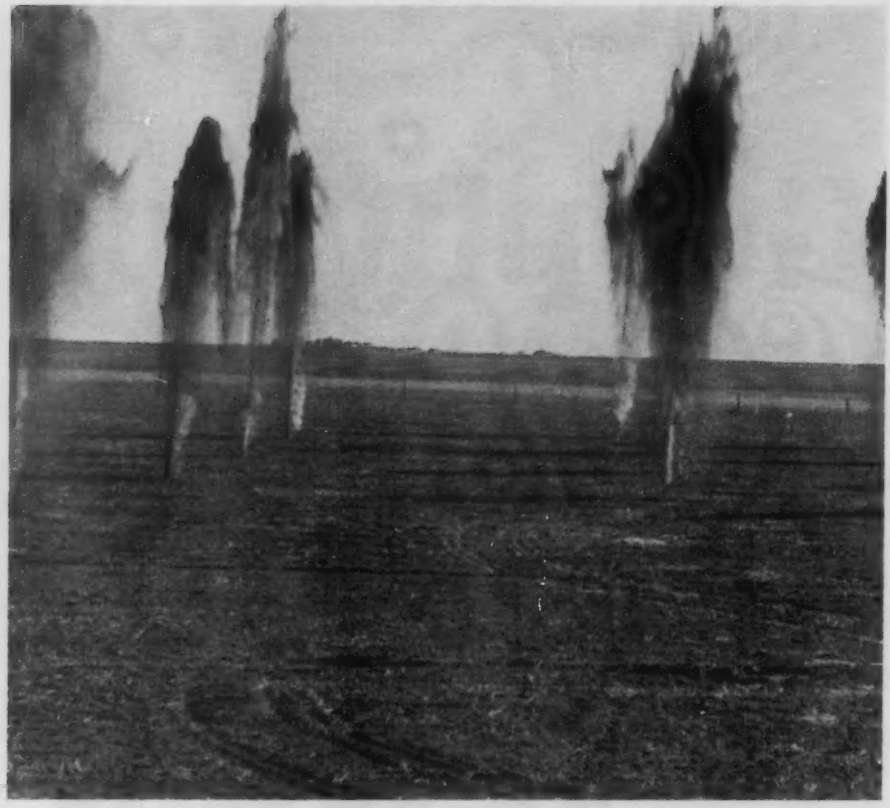

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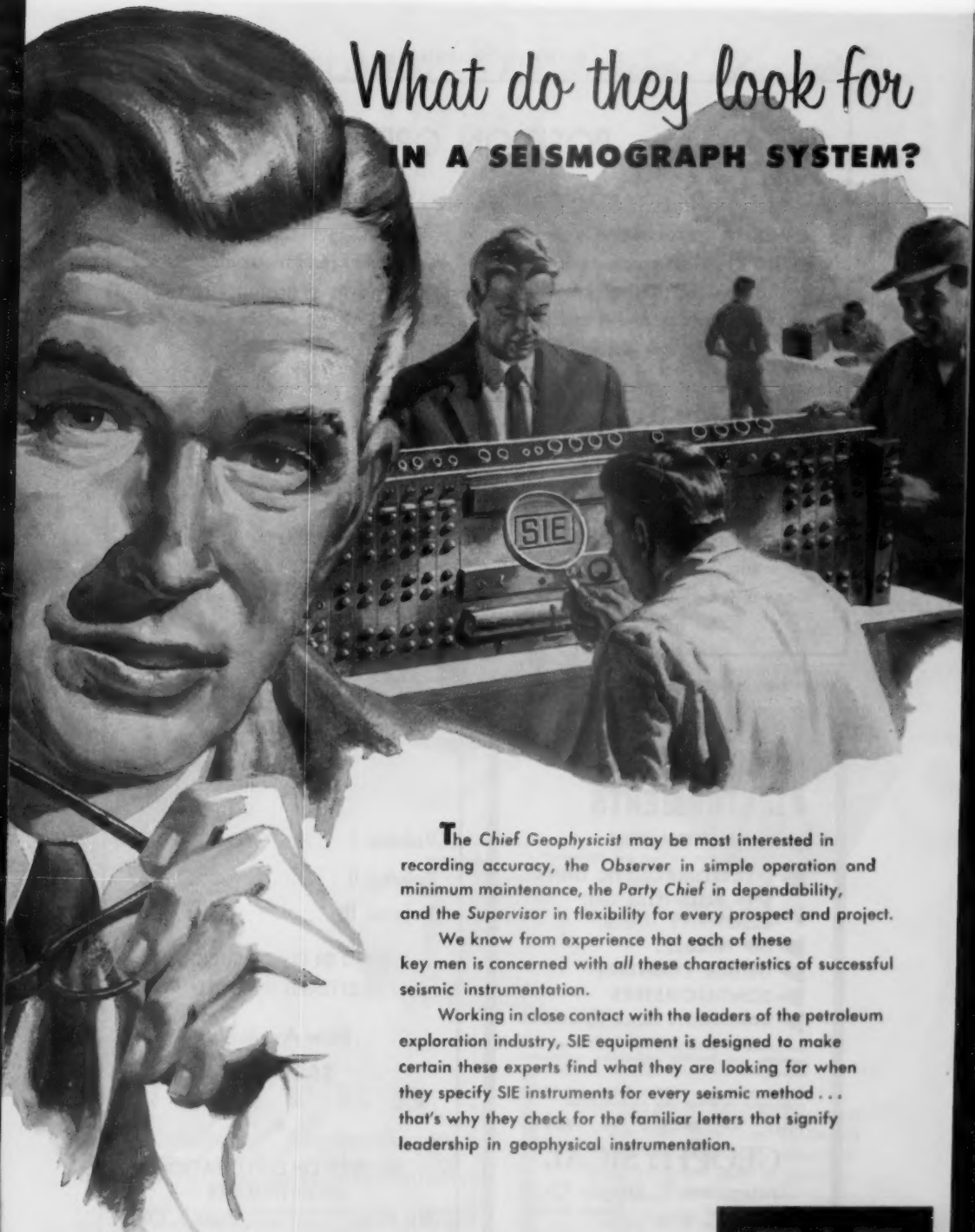

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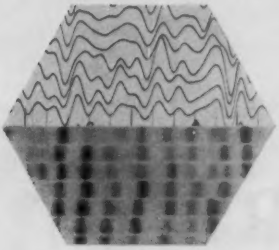

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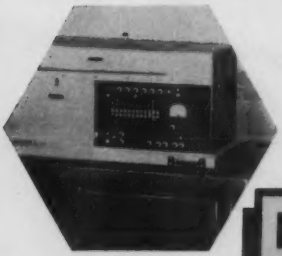

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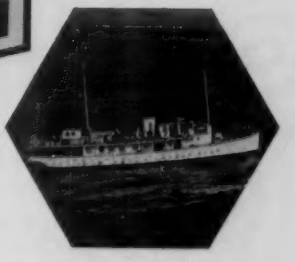

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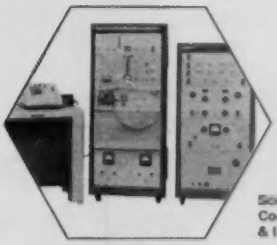

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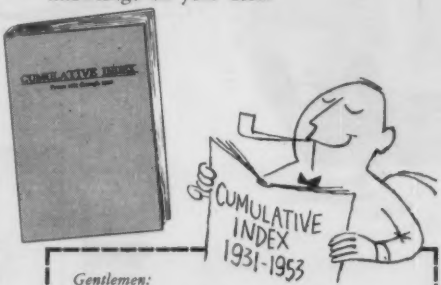

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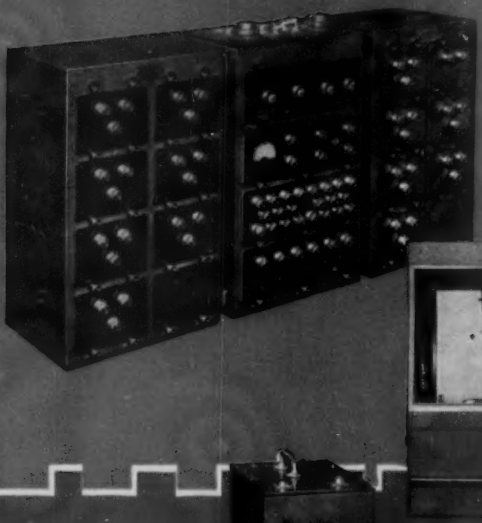

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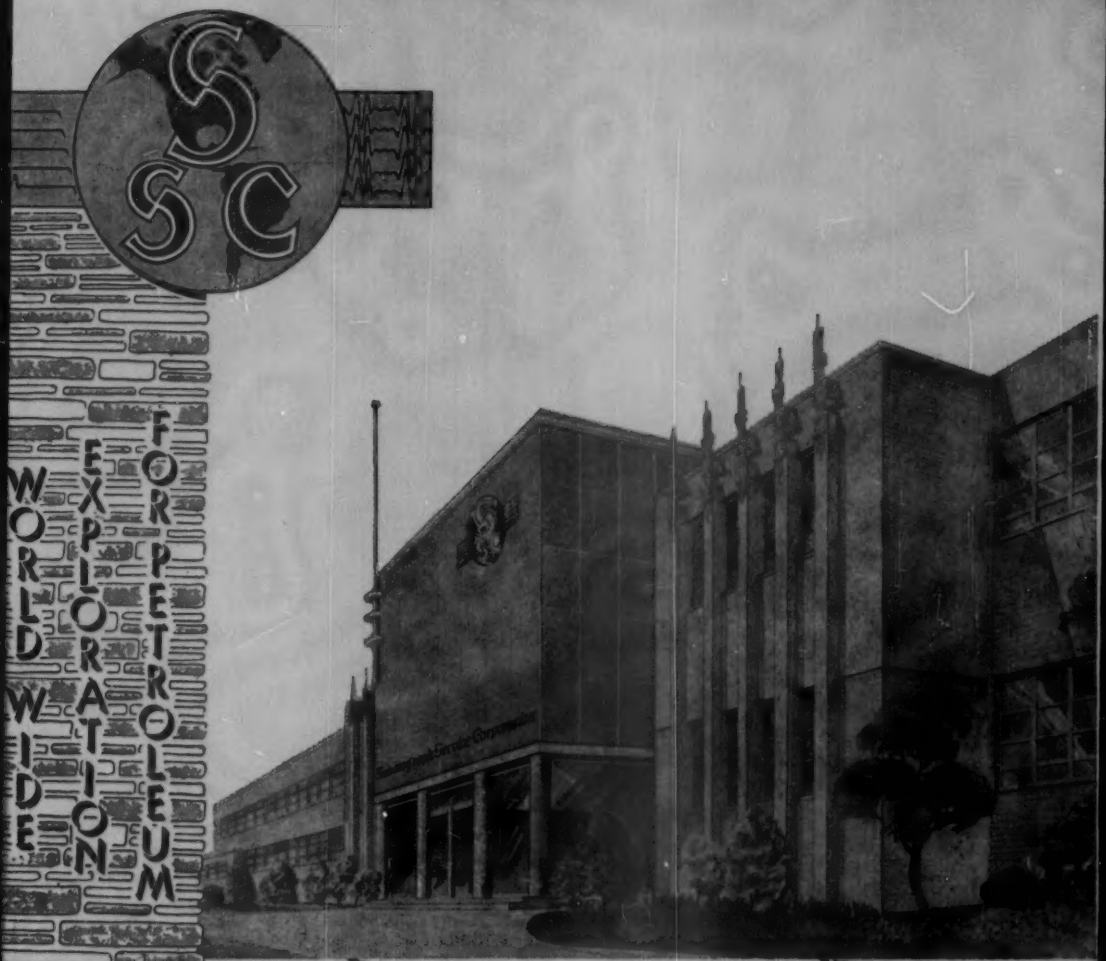

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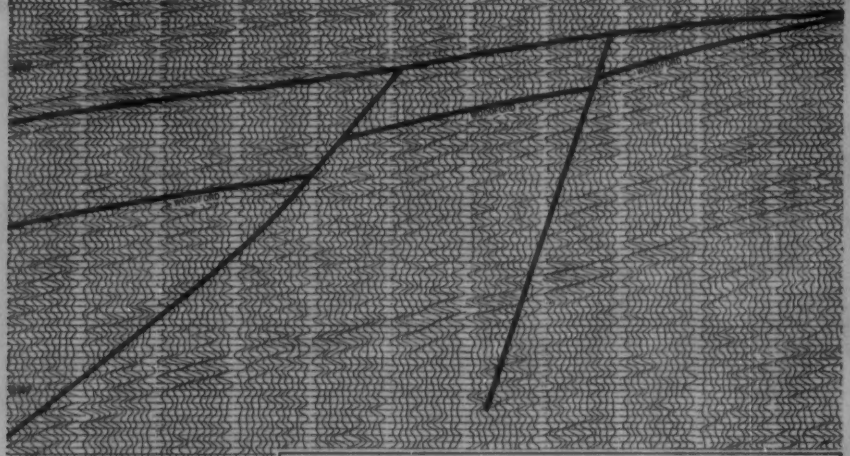

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